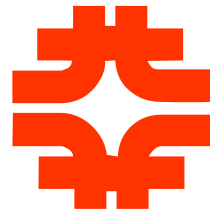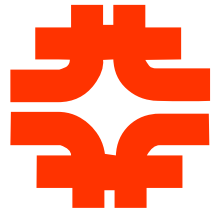# Stochastic Cooling at Fermilab

Dave McGinnis

Workshop on Beam Cooling and Related Topics

Bad Honnef, Germany

May 16, 2001

Antiprotons at FNAL

- Antiprotons are used in the TEVATRON Collider
- Antiproton Production Rate
  - Run 1b 5-7x10^{10}/hour
  - Run 2a 15-20x10^{10}/hour
  - Run 2b 40-60x10^{10}/hour
- Antiprotons are produced by striking a Nickel target with a 120 GeV proton beam
  - 5x10^{12} protons/pulse (Run 2a)
  - Pulse length = 1.6 uS
  - Cycle time = 1.5 Sec
  - r.m.s size = 0.15 mm
- 8 GeV antiprotons are collected by a Lithium Lens
  - 750 T/m
  - 1 cm radius
 - 15 cm long

FNAL Antiproton Source
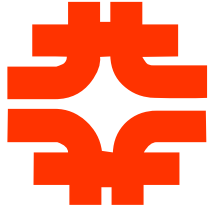
Antiprotons at FNAL

- 8 GeV antiprotons are injected into the Debuncher Ring
  - Admittance = 25 π-mm-mrad
  - Momentum aperture = 4%
  - η = 0.006
  - Debunching reduces the moment spread to 0.3%
    - 5.0 MV @ 53 MHz (h=90)
    - Bucket Height = 230 MeV
    - T_{synch} / 4 ~ 40 turns
  - In 1.5 secs (Run 2a), pre-cooling in the Debuncher reduces
    - Transverse emittance from 25 π-mm-mrad (95% full width) to 4 p-mm-mrad
   - Mometum spread from 0.3% to 0.08%
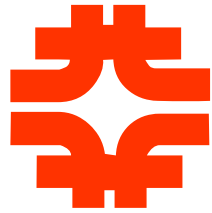
Antiprotons at FNAL

- The pre-cooled antiprotons are injected into the Accumulator
    - Aperture = 8 π-mm-mrad
    - Momentum aperture ~ 2%
    - $\eta=0.012$ (Run 2a) ($\eta=0.022$ – Run 1b)
- The beam is moved from the injection orbit to the stacking orbit with a RF system
    - h=84 (53 MHz)
    - bucket area of 0.27 eV-sec
- The beam is momentum stacked into the core with the StackTail momentum cooling system
    - Exponential gain slope ~ 12 MeV
   - Momentum aperture of Stacktail system = 0.7%
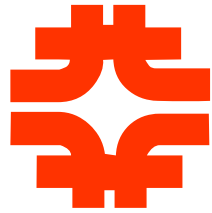
Accumulator Orbits
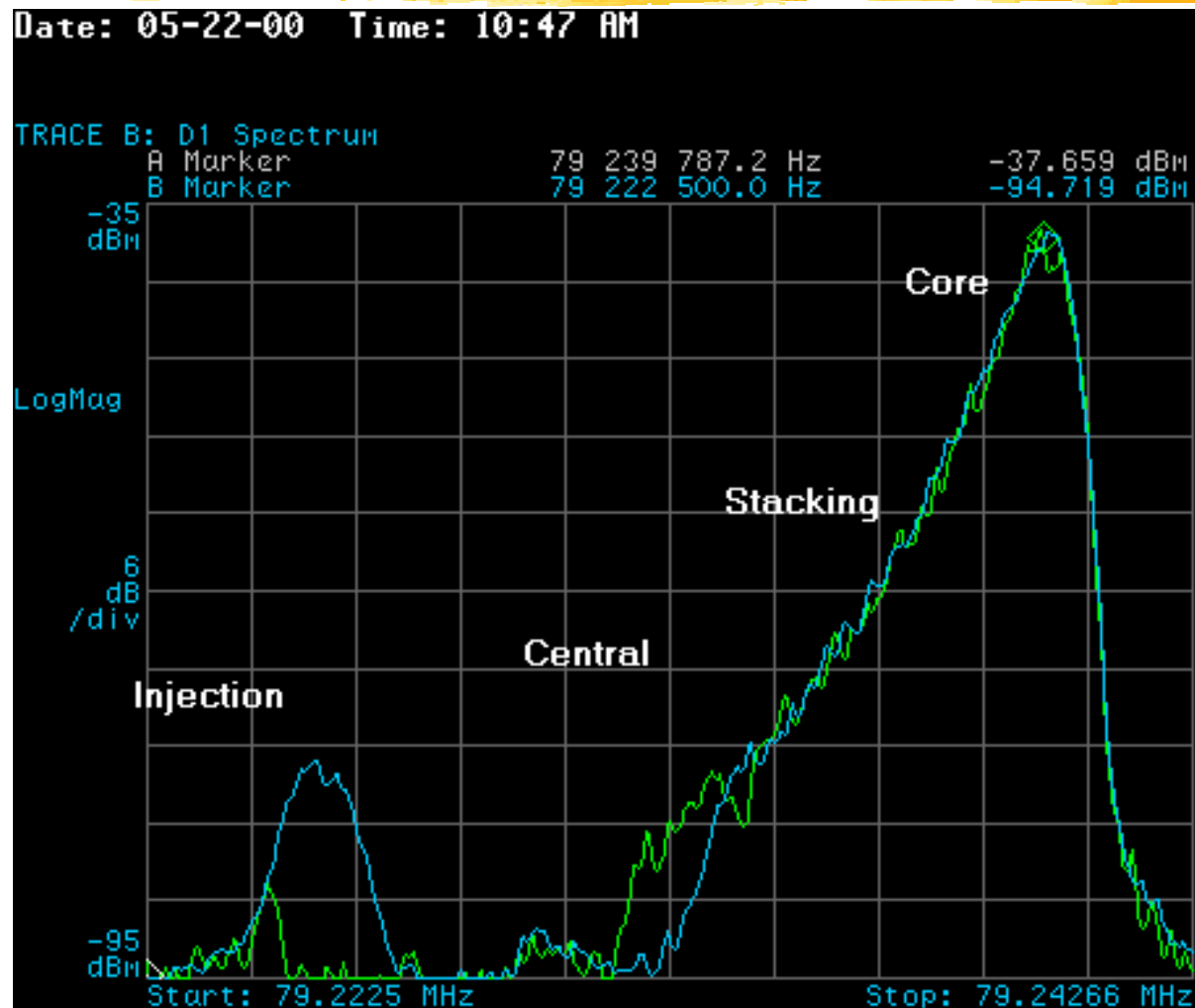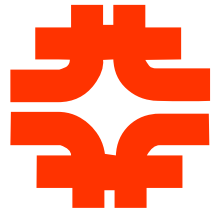
Antiprotons at FNAL

- Antiprotons are accumulated and cooled into the Accumulator Core
  - Run 2a without the Recycler
    - Accumulate 150×10^{10} antiprotons
    - Send all the antiprotons to the TEVATRON via the Main Injector every 8-10 hours
  - Run 2a with the Recycler
    - Accumulate $20\text{-}40 \times 10^{10}$ antiprotons
    - Send all the antiprotons in the Accumulator to the Recycler every 1-2 hours
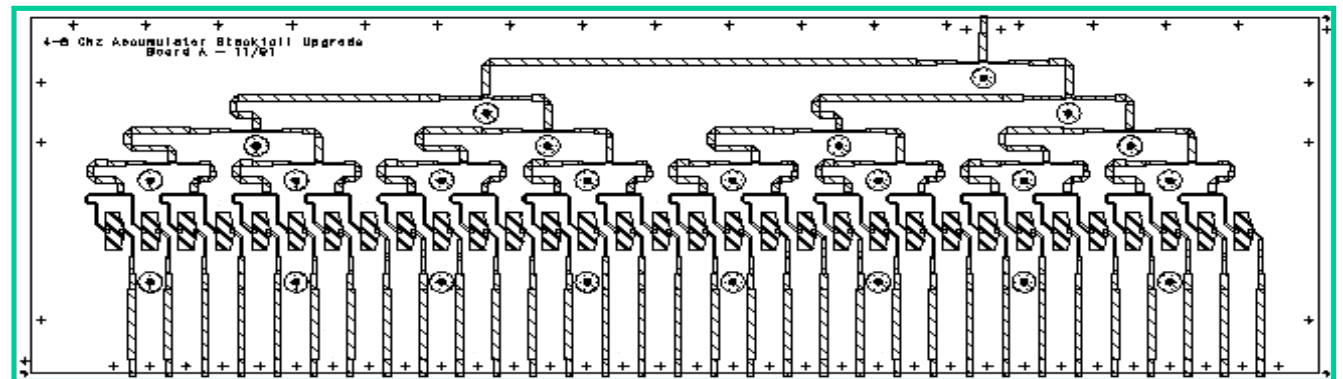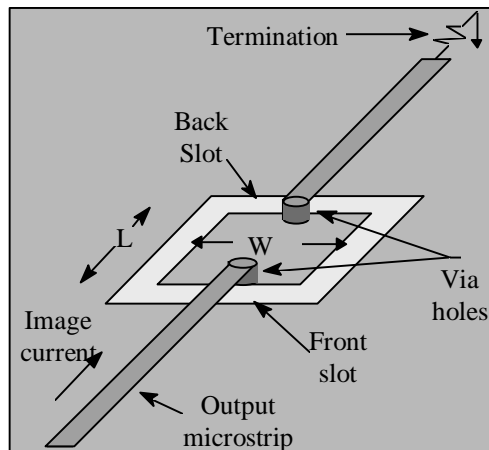   - Time-stack antiprotons in the Recycler using barrier buckets and stochastic cooling.
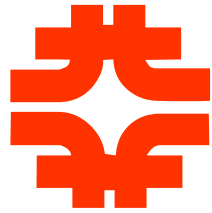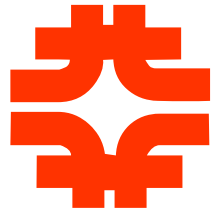
Debuncher Stochastic Cooling

- **Original design for Run 2a Upgrade**
  - Keep 2-4 GHz bandwidth using stripline electrodes
  - Cool pickups to 10 K
  - Plunge arrays from 24 π-mm-mrad to 5 π-mm-mrad
- **Upgrade for Run 2b**
  - During Run 2b the increase in the number of antiprotons/pulse should increase by a factor of 3.5 over Run 2a
    - Slip Stacking - 1.8x
    - Increased lens gradient - 1.3x
    - Increased collection aperture – 1.5 x
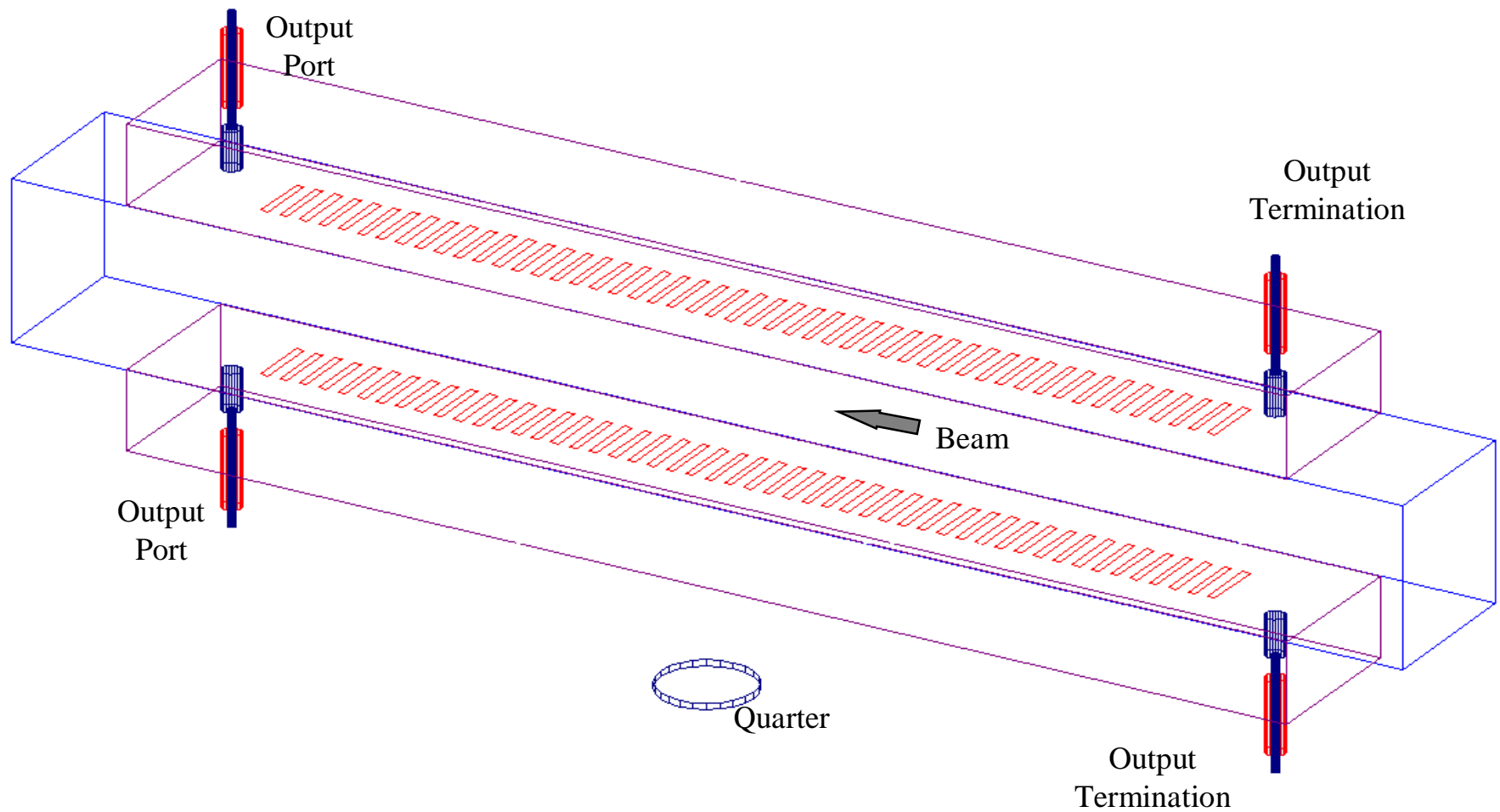 - With this increase of antiprotons/pulse, a 2-4 GHz system would become bandwidth limited
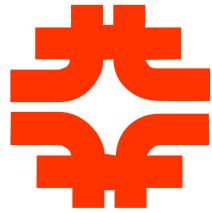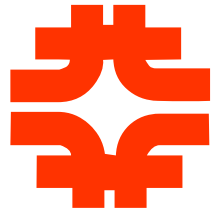
Binary Combining of Planar Loops

- Many low sensitivity broadband loops are combined in binary arrays to form a broadband array.
  - Binary combiner boards can only work if there are no waveguide modes in the beam pipe.
  - Combiner boards insertion loss increases dramatically as the frequency is increased
    - More levels of combining because more electrodes / length
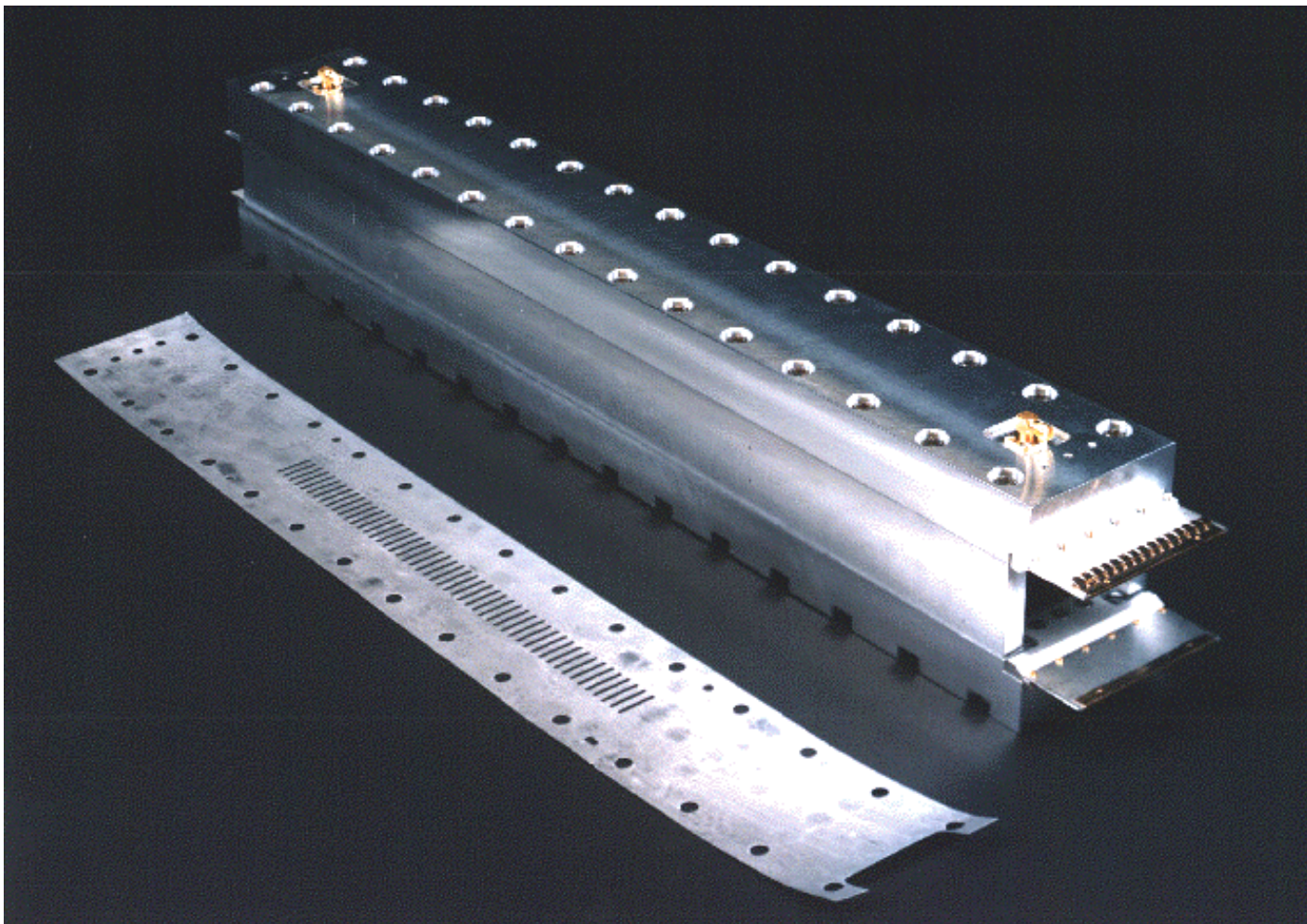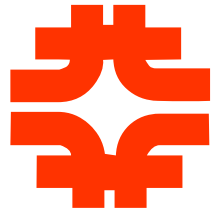   - Line loss / length also increases with frequency

Termination

Back Slot

L

W

Image current

Front slot

Via holes

Output microstrip

4-8 GHz Accumulator Stacktail Upgrade
Board A — 11/91

Slotted Slow Wave Structure

Output Port

Output Port

Output Termination

Output Termination

Beam

Quarter

Slotted Slow Wave Structure

Slotted Slow Wave Structure

- Slots carved in a waveguide wall will slow down the <u>phase</u> velocity of a wave in the waveguide.
  - ❑ The reduction in phase velocity is a function of the slot length and width and the spacing between slots.
  - ❑ The coupling of the slots to the beam is proportional to the slot length.
- When the reduced phase velocity of the waveguide matches the beam velocity, the coupling of the slots will add constructively.
- In this slow-wave mode,
  - ❑ The gain of the array is proportional to the number of slots. (as compared to a binary combiner board where the gain is proportional to the square root of the number of slots.)
  - ❑ The bandwidth of the array is inversely proportional to the number of slots.
- This is similar to the 8-10 GHz CERN design of the slow wave ridged pickup array used for bunched beam cooling in the SPS.
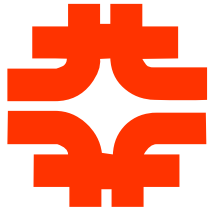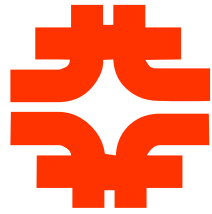
Narrow Band Channels

- For optimum sensitivity and array length, the 4-8 GHz band is broken up into 4 kicker bands and 8 pickup bands
- Each slot array is narrowband (< 1.0 GHz) but tuned to a separate center frequency
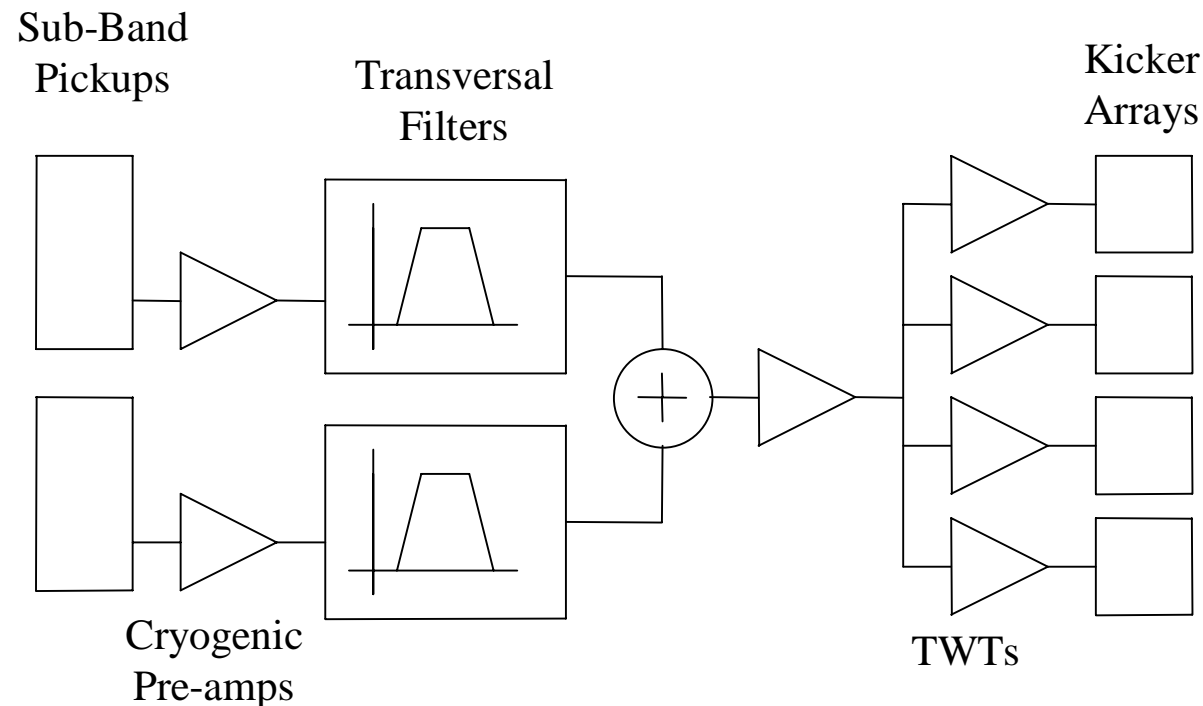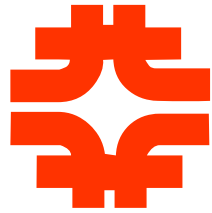
Pickup Bands
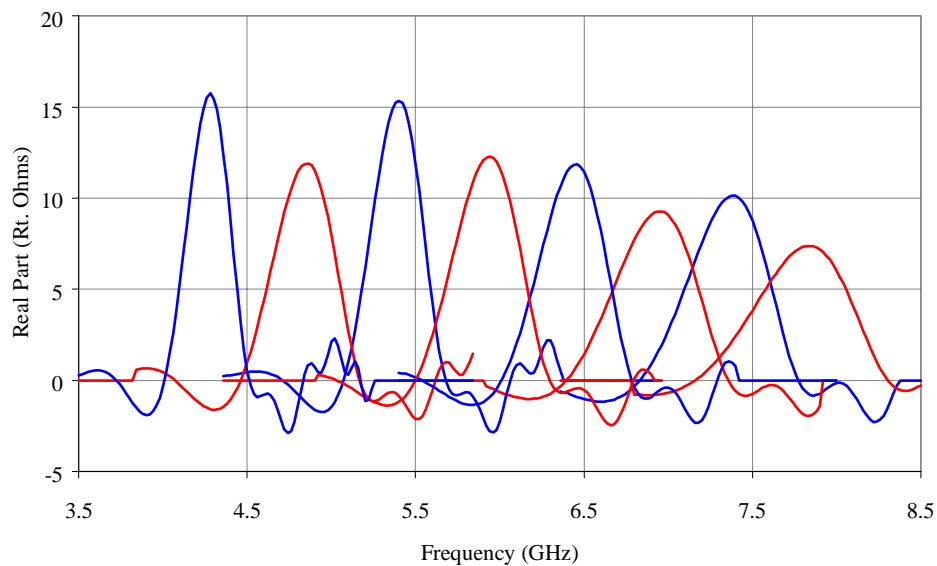
Pickup Bands
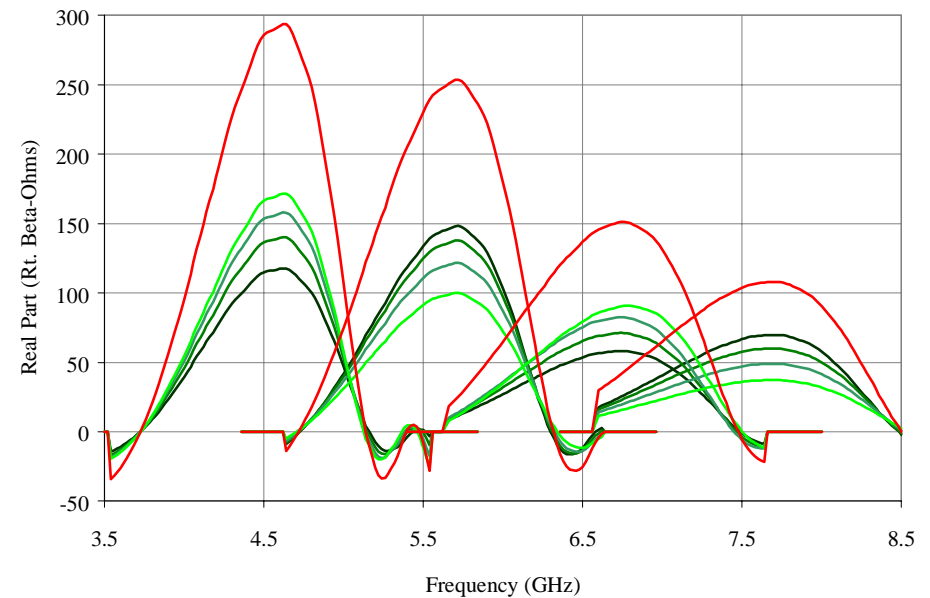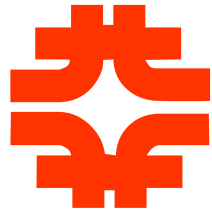
Simple schematic of components in a single band.

- Using two pickup bands for every kicker band eliminates a lossy stripline combiner inside the pickup cryogenic vacuum tank but requires narrowband front-end filters to reduce noise power overlap

Sub-Band Pickups

Transversal Filters

Kicker Arrays

Cryogenic Pre-amps

TWTs

Transversal Filter Response
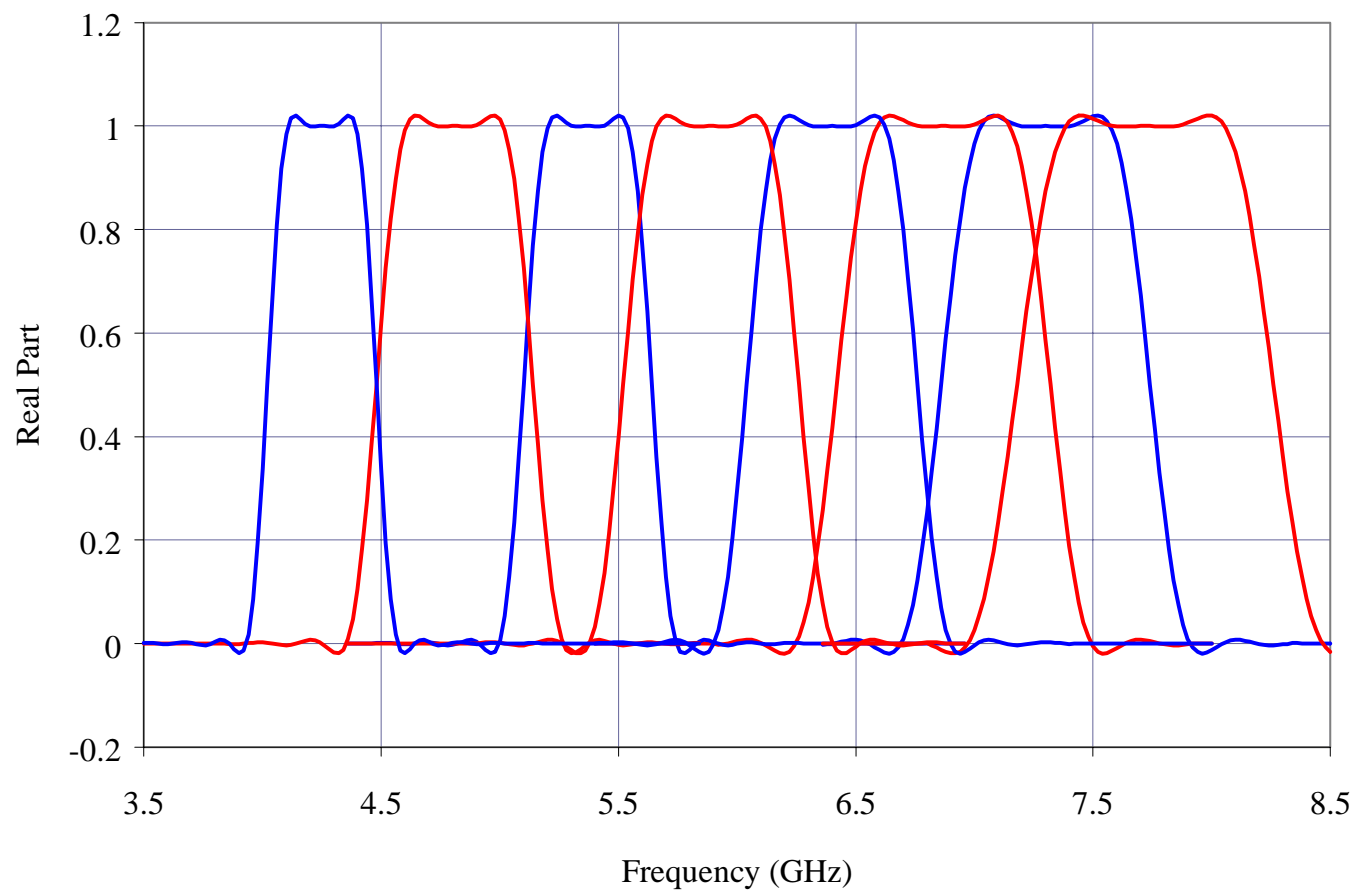
4-8 GHz Debuncher Stochastic Cooling System

- 4-8 GHz of Bandwidth
  - ❑ 8 Narrowband Pickup channels
  - ❑ 4 Narrowband Kicker Channels
- Physical front end temperature = 10K
- Front end microwave noise temperature ~ 30K
- Pickup and kicker antenna arrays
  - ❑ Fixed 40 π mm-mrad, slot coupled, slow wave, waveguide arrays
- Kicker Power
  - ❑ Transverse - 4 TWT's per kicker band at 150 Watts/ TWT
  - ❑ Momentum - 8 TWT's per kicker band at 150 Watts/ TWT
  - ❑ Total Power = 9600 Watts
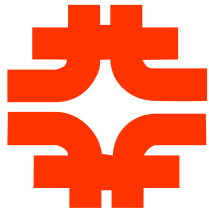
Projected Debuncher Cooling Performance

Measured Longitudinal Signal to Noise

Measured Beam Power Signal to Noise
(Normalized to 10E+06 Particles)
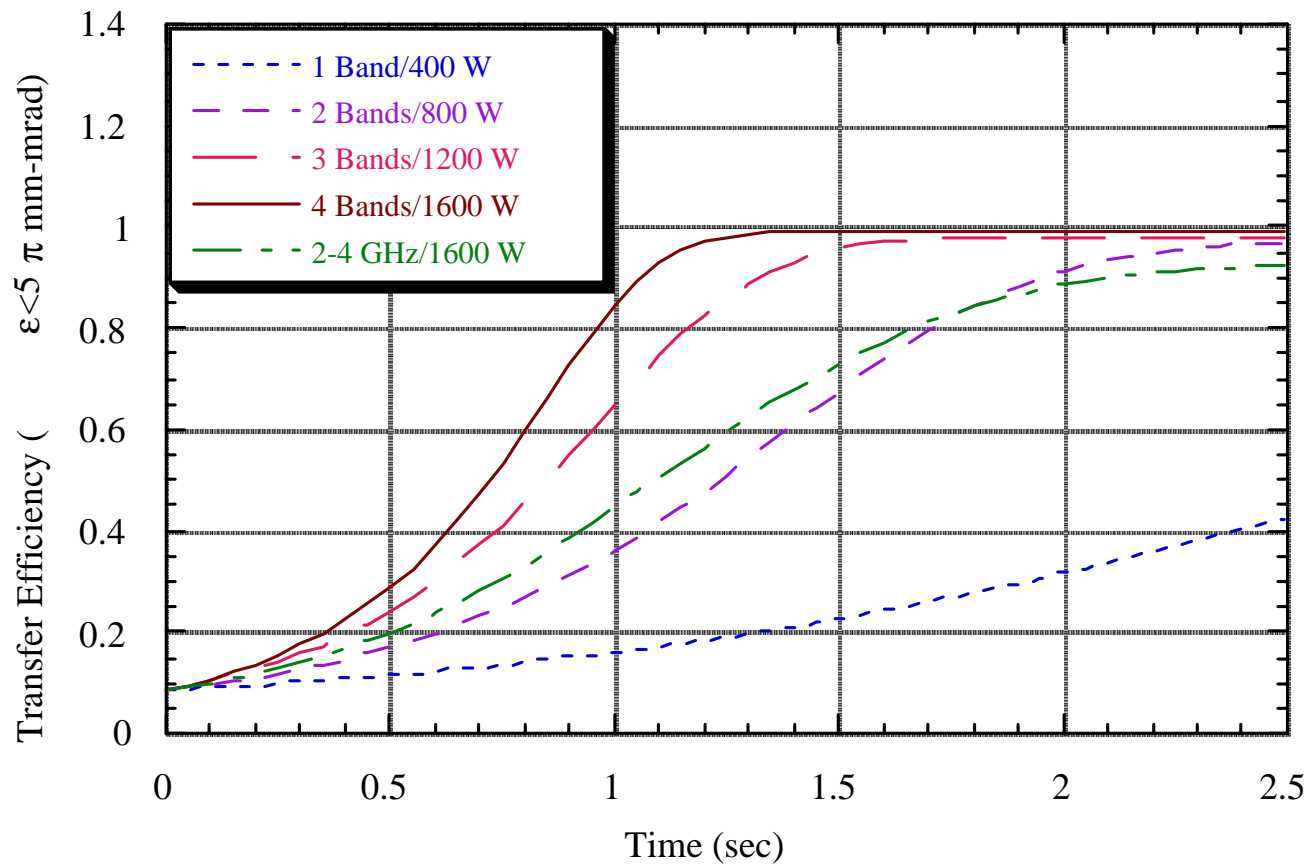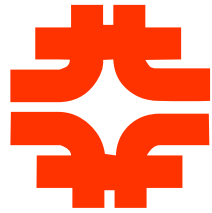
Measured Longitudinal Pickup Impedance

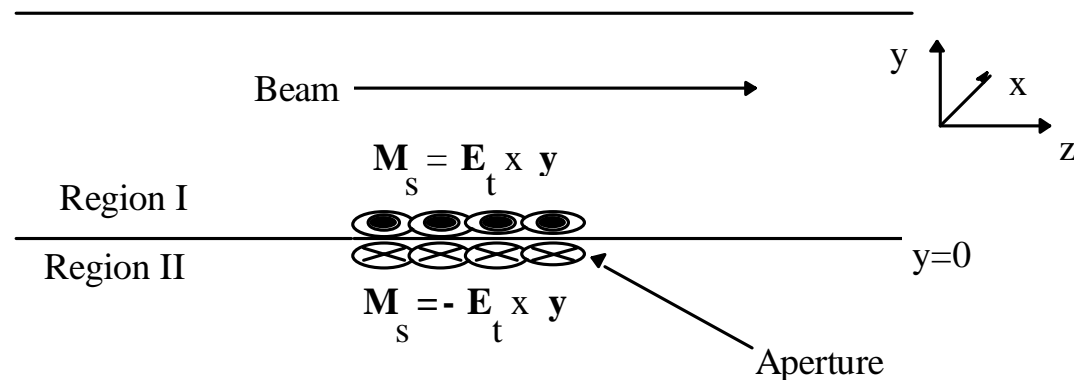Measured Vertical Sum Mode Pickup Response
(Effective Temperature = 30K)
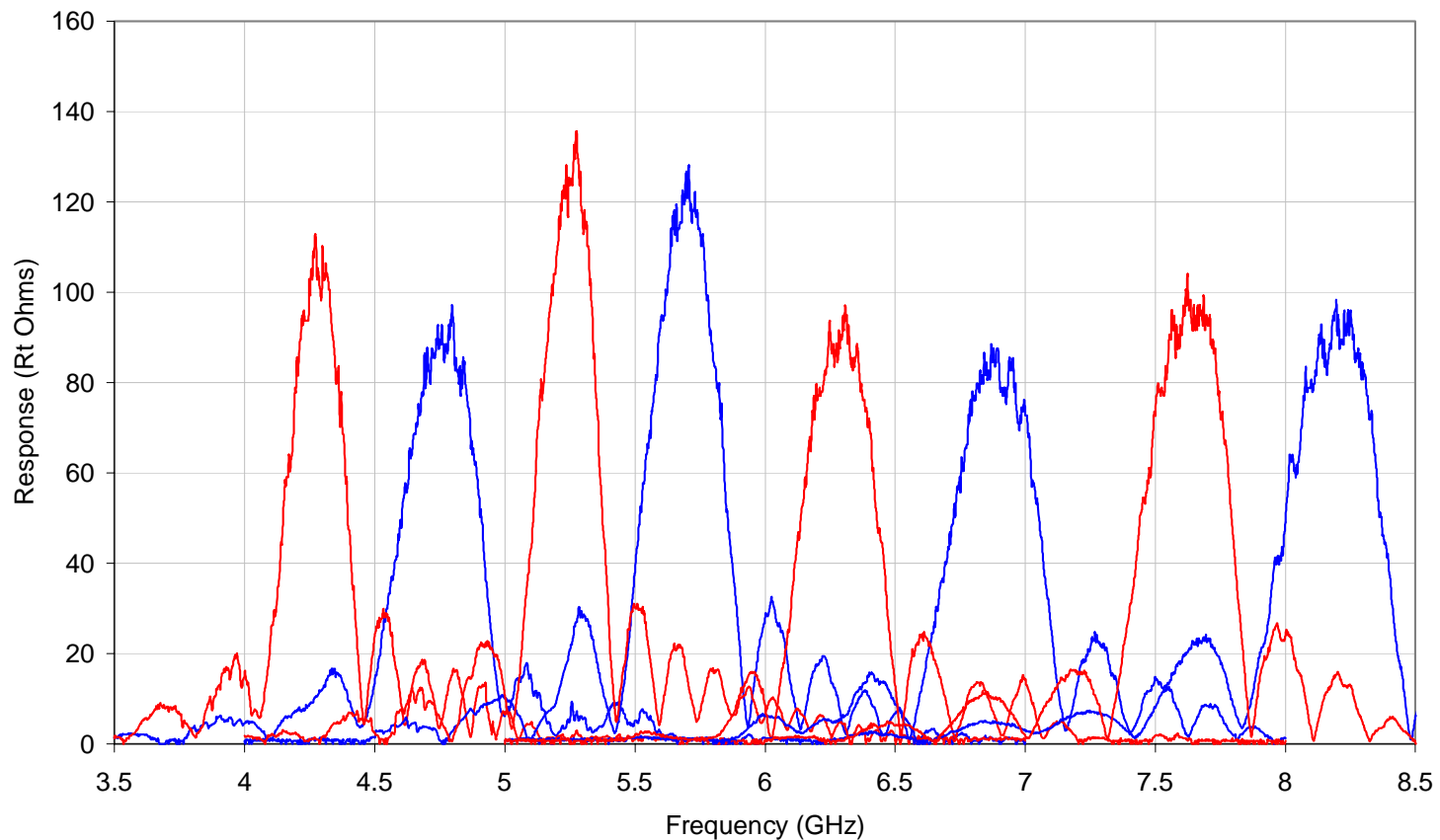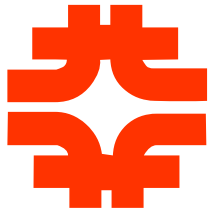
Calculated Longitudinal Impedance
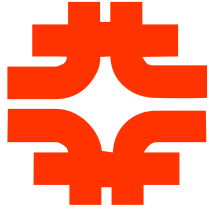

Calculated
Vertical Sum Mode Pickup Response
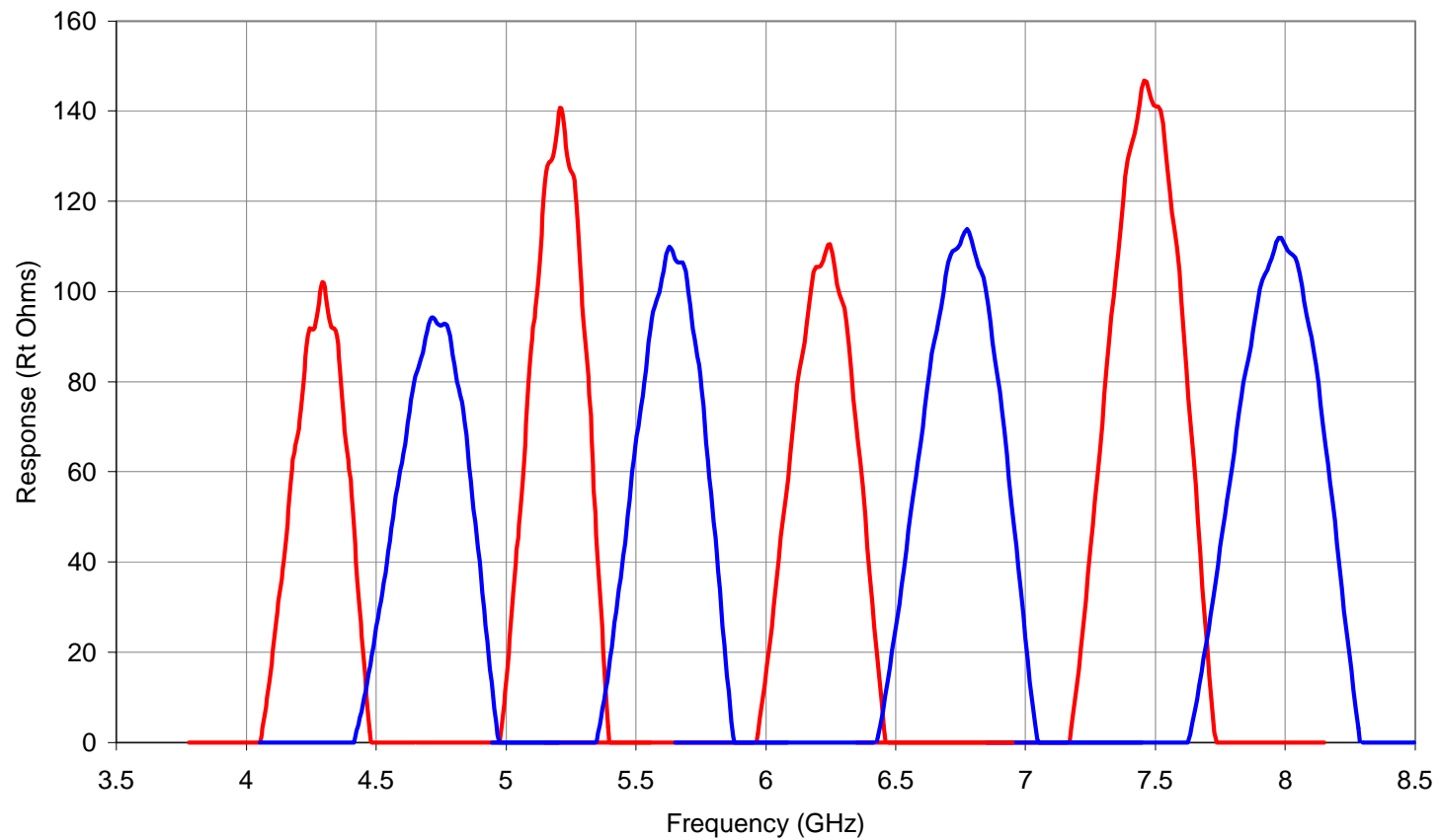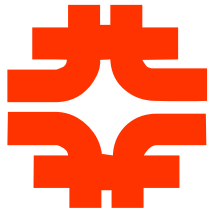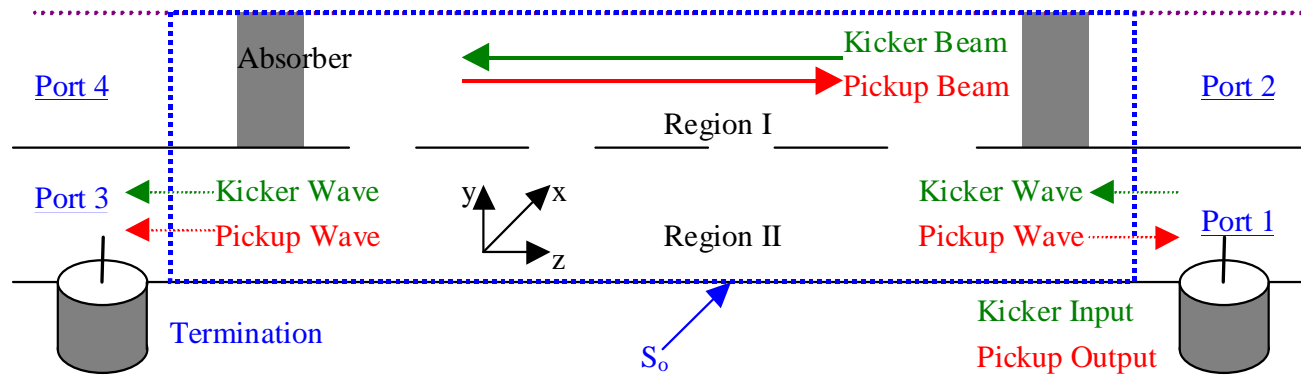
Moment Methods for Excited Slot Coupled Waveguides

Beam →

y, x, z

$\mathbf{M}_s = \mathbf{E}_t \times \mathbf{y}$

Region I

Region II

$\mathbf{M}_s = -\mathbf{E}_t \times \mathbf{y}$

y=0

Aperture

$$\vec{H}_{t\;2}^{(\text{inc})} - \vec{H}_{t\;1}^{(\text{inc})} = \vec{H}_t^{(1)}\left(\vec{E}_t \times \hat{y}\right) + \vec{H}_t^{(2)}\left(\vec{E}_t \times \hat{y}\right)$$

$$\vec{E}_t = \hat{x}\sum_n E_{x_n}\,\theta_n(x,z) + \hat{z}\sum_n E_{z_n}\,\psi_n(x,z)$$

$$\left\langle \phi_m \left| H_{x\;1}^{(\text{inc})} \right. \right\rangle - \left\langle \phi_m \left| H_{x\;2}^{(\text{inc})} \right. \right\rangle = \sum_n \left(\left\langle \phi_m \left| H_x^{(1)} \right| \psi_n \right\rangle + \left\langle \phi_m \left| H_x^{(2)} \right| \psi_n \right\rangle \right) E_{z_n}$$

Reciprocity for Kicker Impedance

$$\oiint_{S_o}\left(\vec{E}^p \times \vec{H}^k - \vec{E}^k \times \vec{H}^p\right) \bullet \hat{n}dS = \iiint_v \left(\vec{H}^k \bullet \vec{M}^p - \vec{E}^k \bullet \vec{J}^p\right)dv$$

$$\vec{J}^p = \hat{y}\frac{i_b}{2}\delta(x - x_b)\delta(y - y_b)e^{-j\kappa z}$$

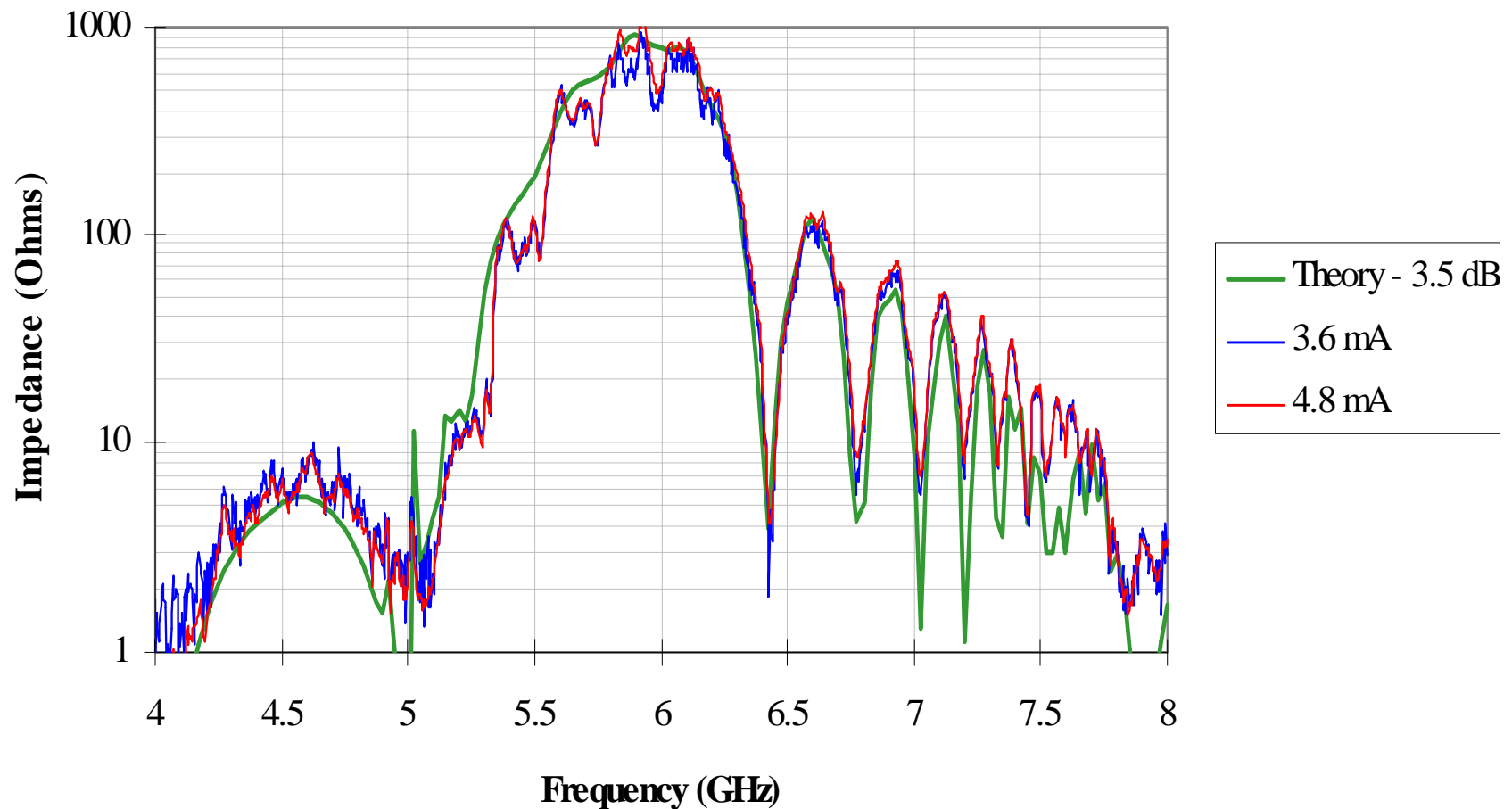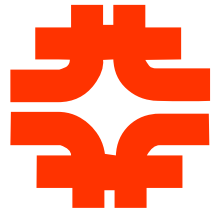$$\vec{M}^p = \hat{x}\eta\frac{i_b}{2}\delta(x - x_b)\delta(y - y_b)e^{-j\kappa z}$$
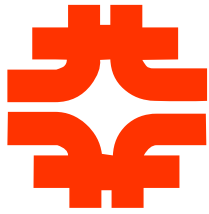
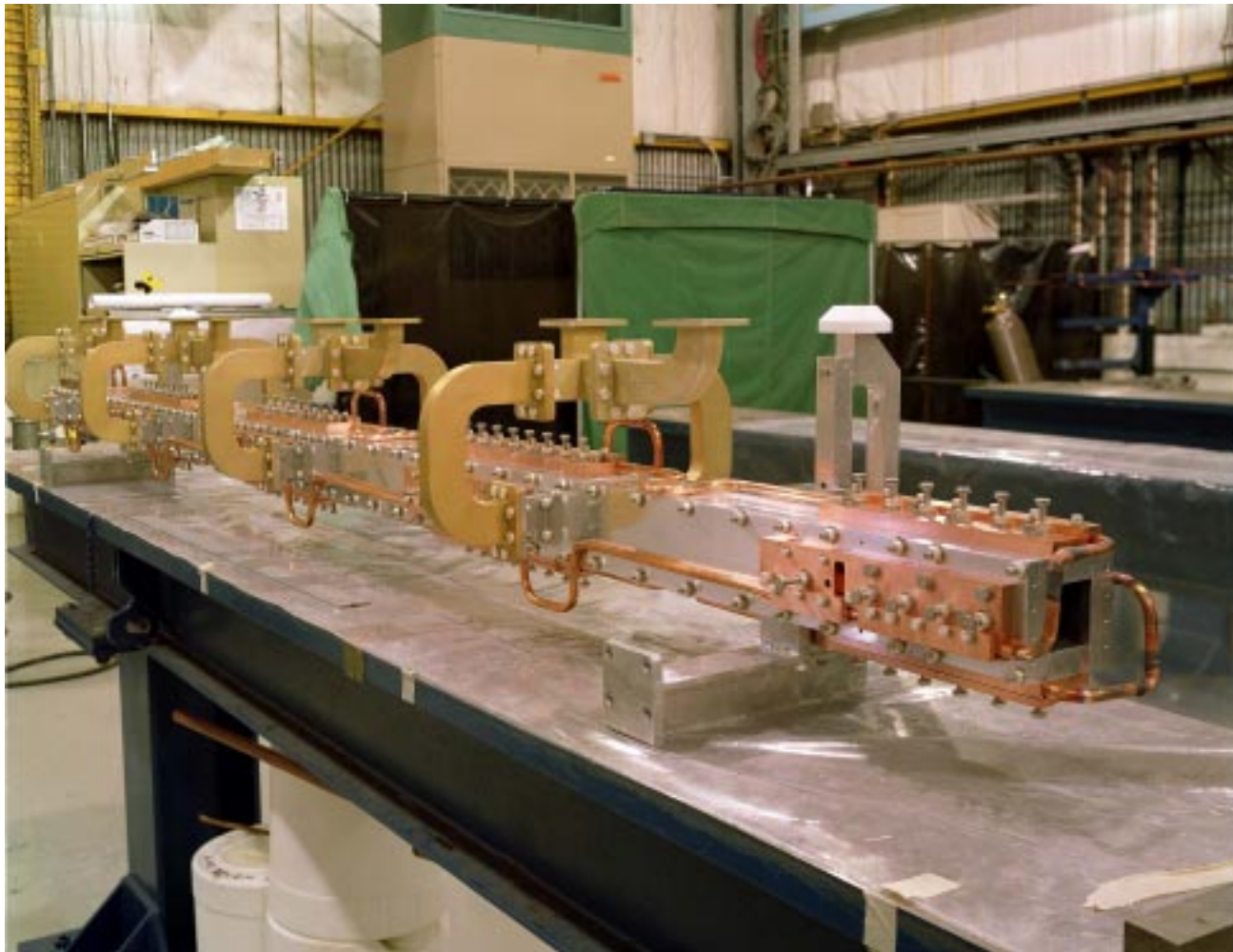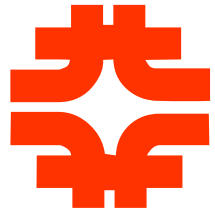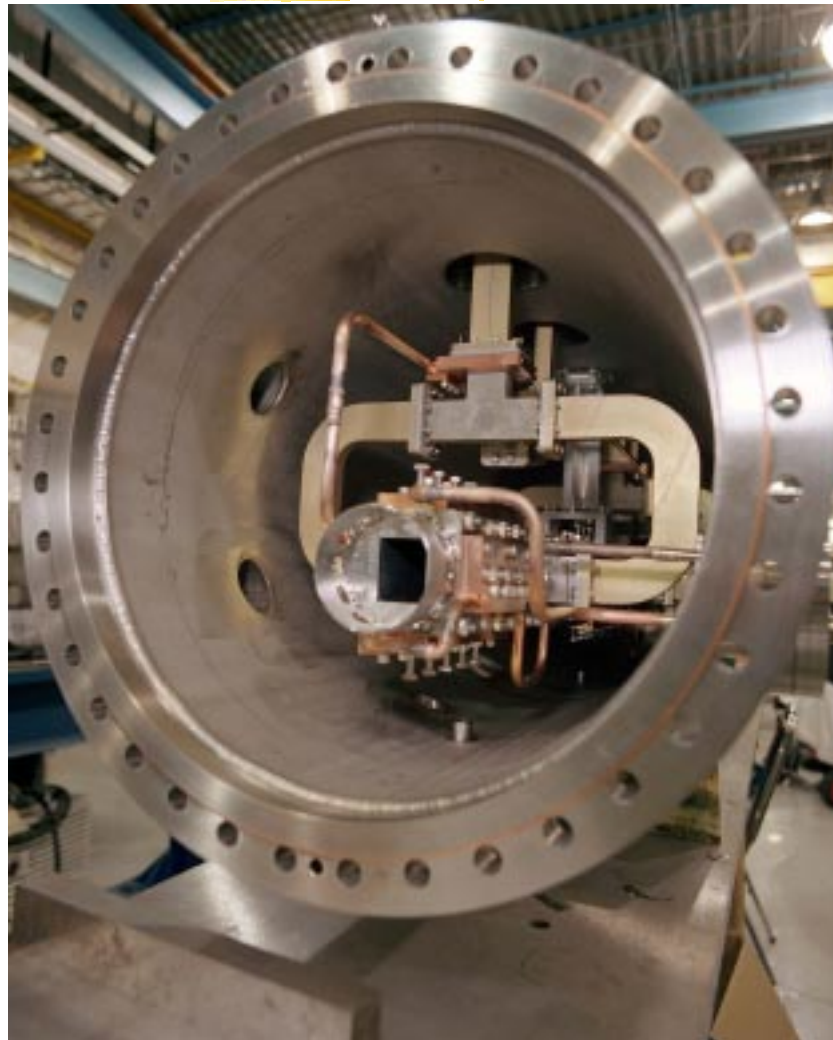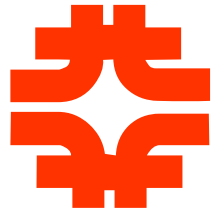# Difference Mode Theory and Calculations
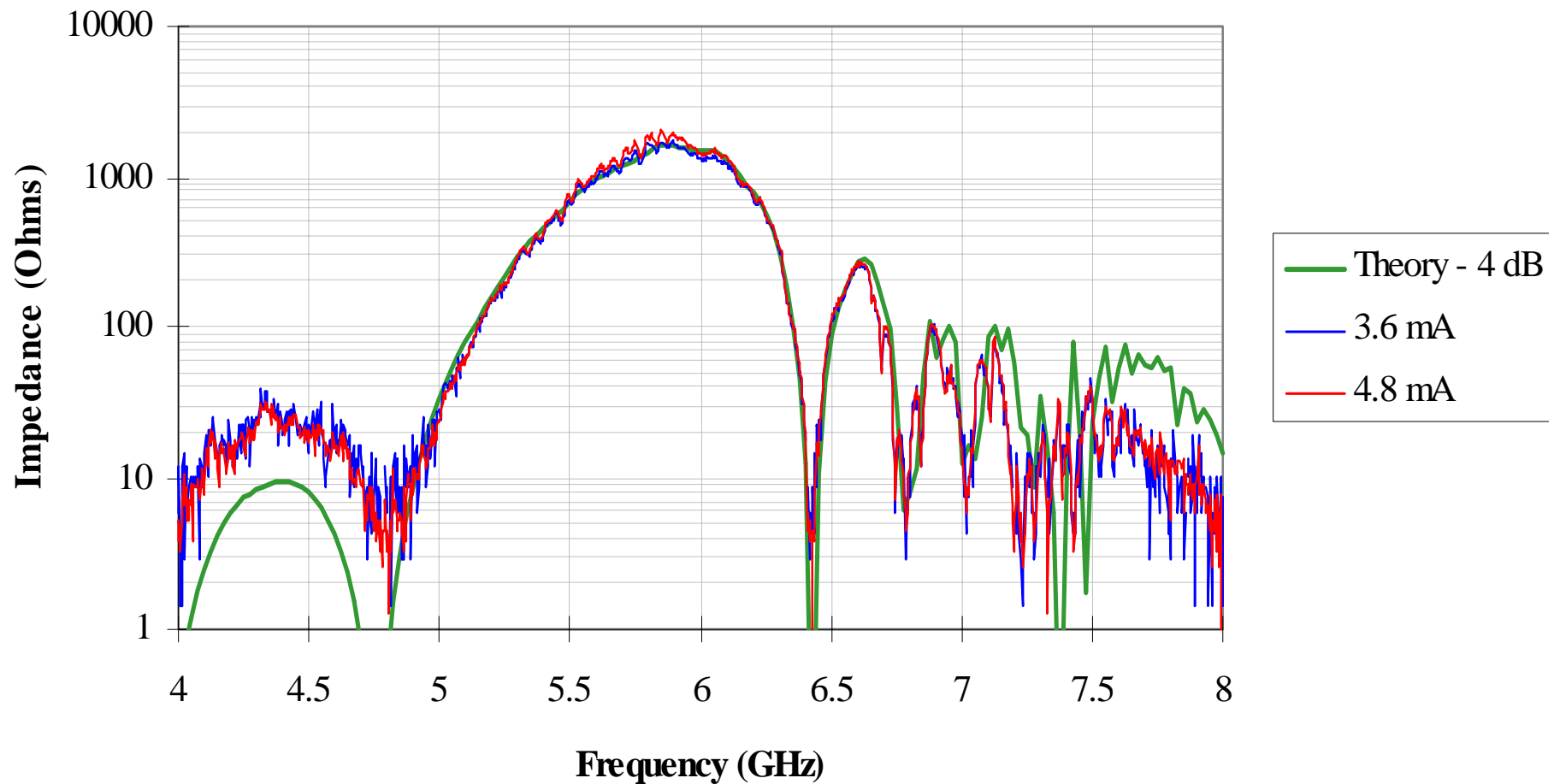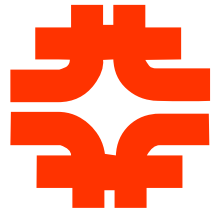
Sum Mode Theory and Calculations

Debuncher Bands 3 & 4 Kicker Tanks

Debuncher Bands 3 & 4 Kicker Tanks
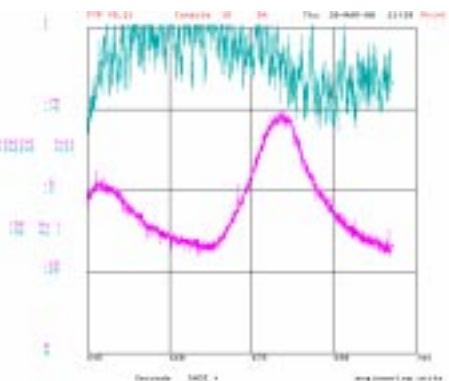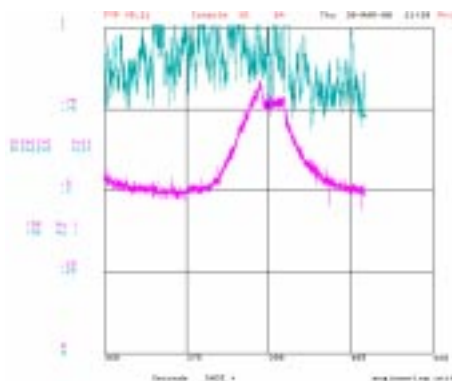
Debuncher Cryogenic Pre-Amp
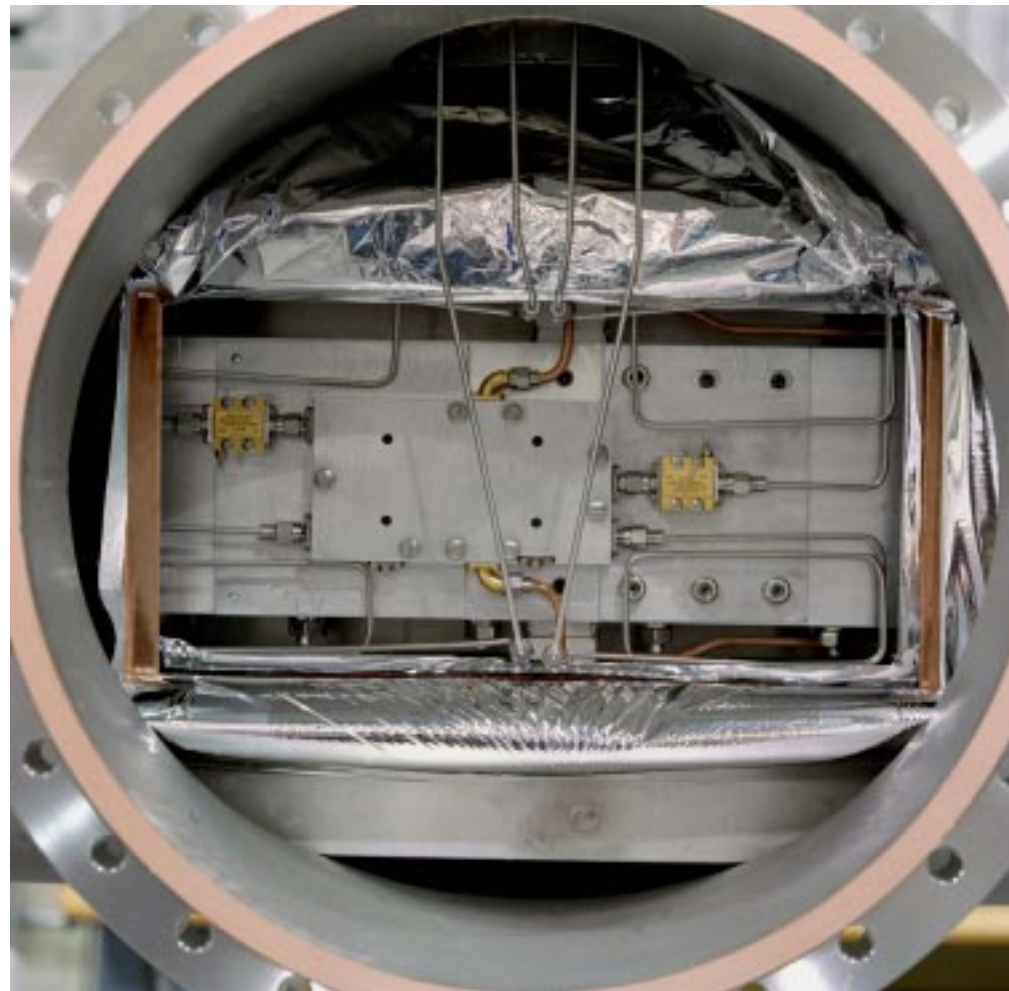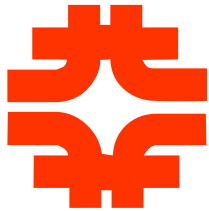
Debuncher Cooling Rates

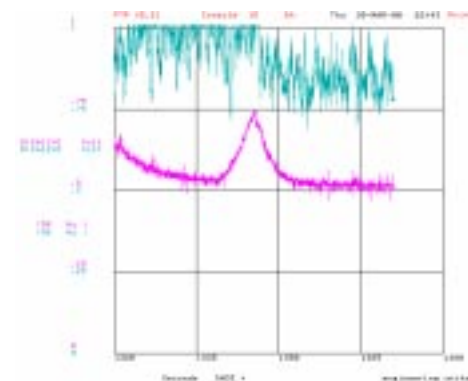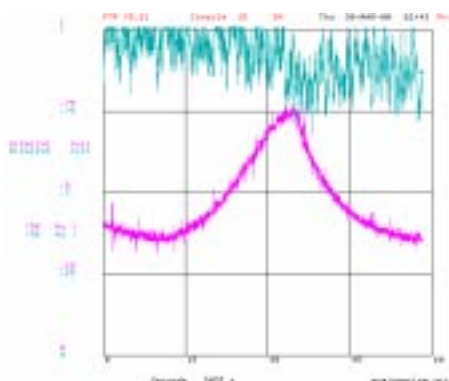|	Band 1	Band 2	Both

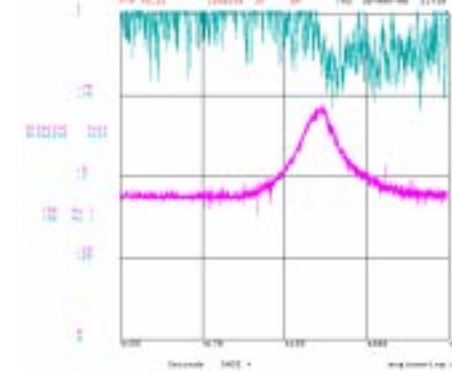**Horizontal**

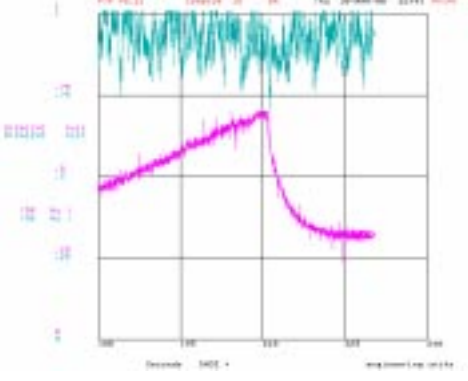$\tau = 4.3$ sec

$\tau = 3.6$ sec

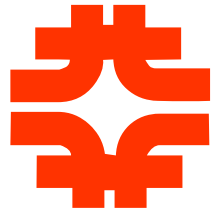$\tau = 2.3$ sec

Vertical

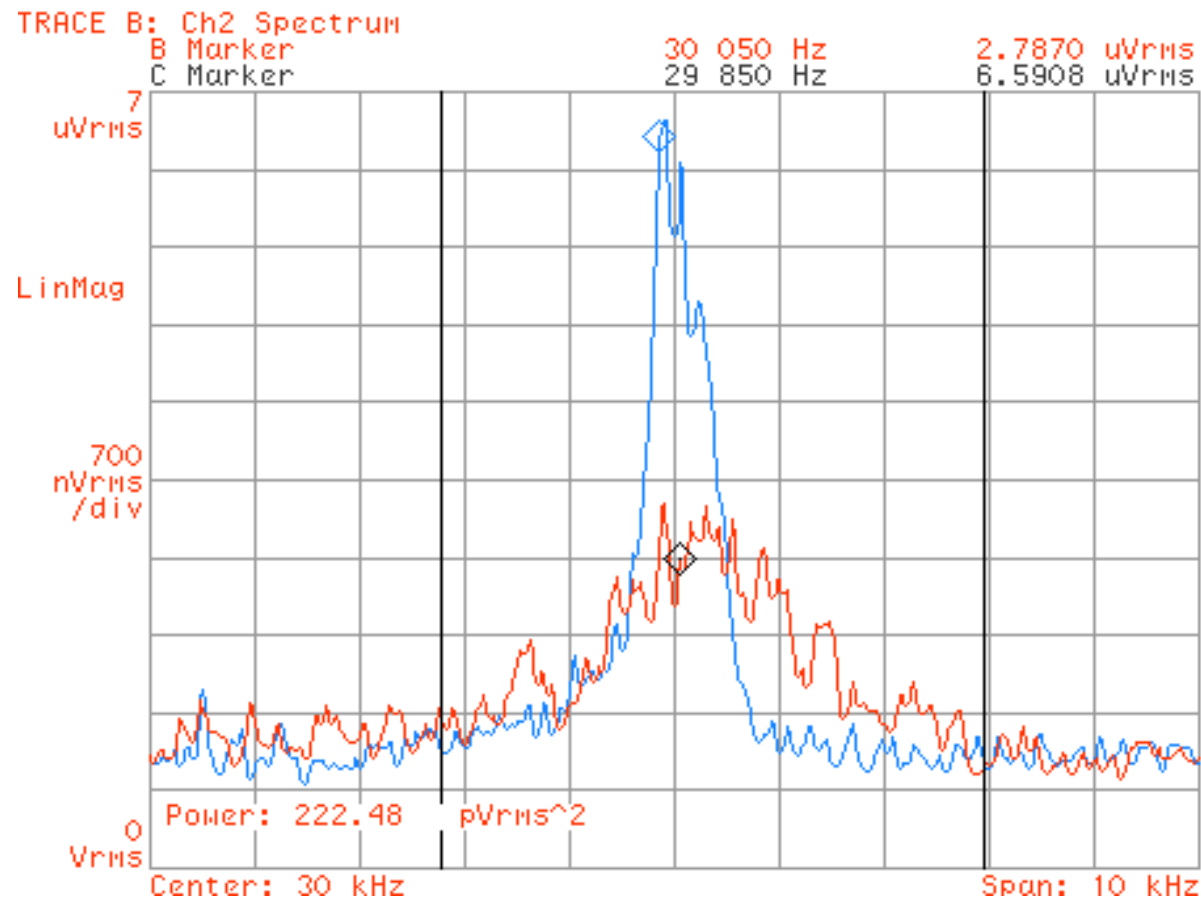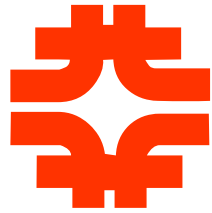$\tau = 6.5$ sec

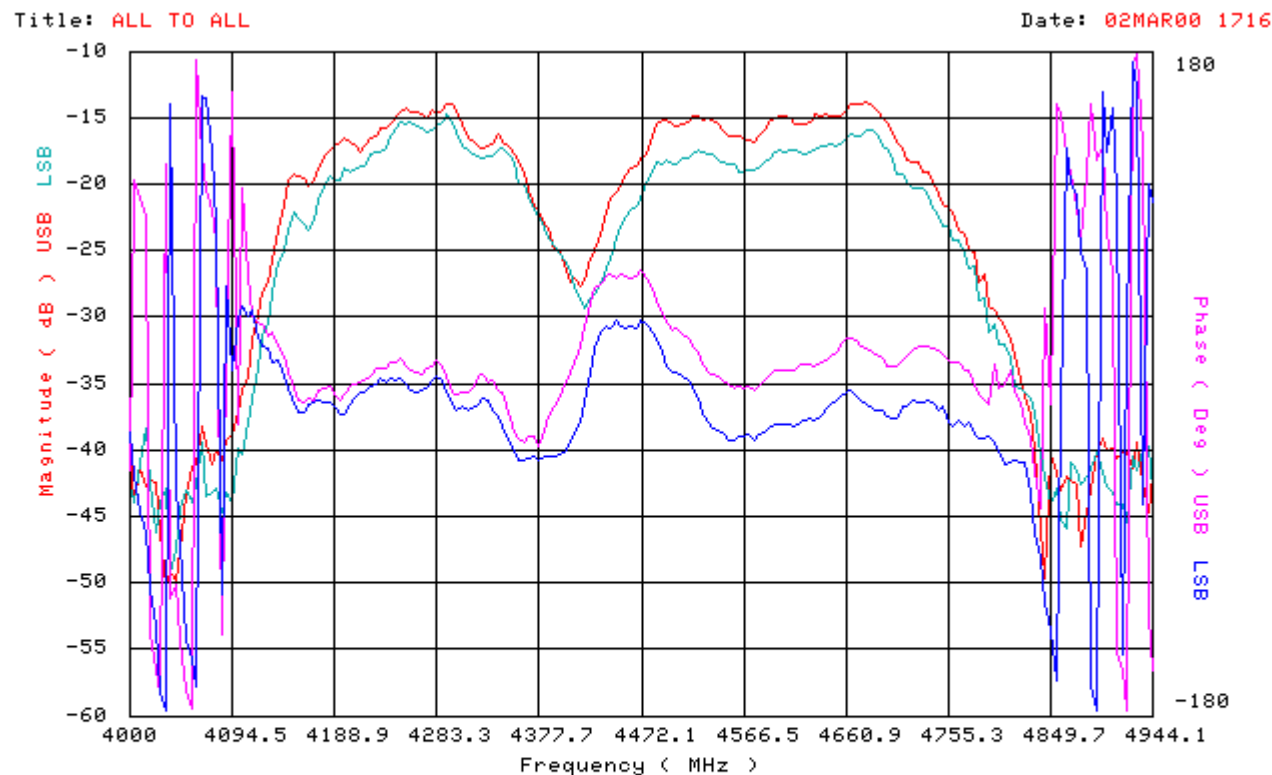
$\tau = 4.7$ sec

$\tau = 2.5$ sec

Debuncher Momentum Cooling

- Accumulator longitudinal Schottky signal on the Injection orbit with Debuncher Momentum Bands 1 & 2 Cooling on/off
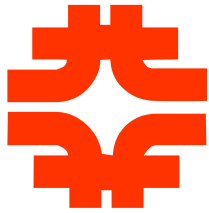
Debuncher Band 1 Beam Transfer Function Measurement

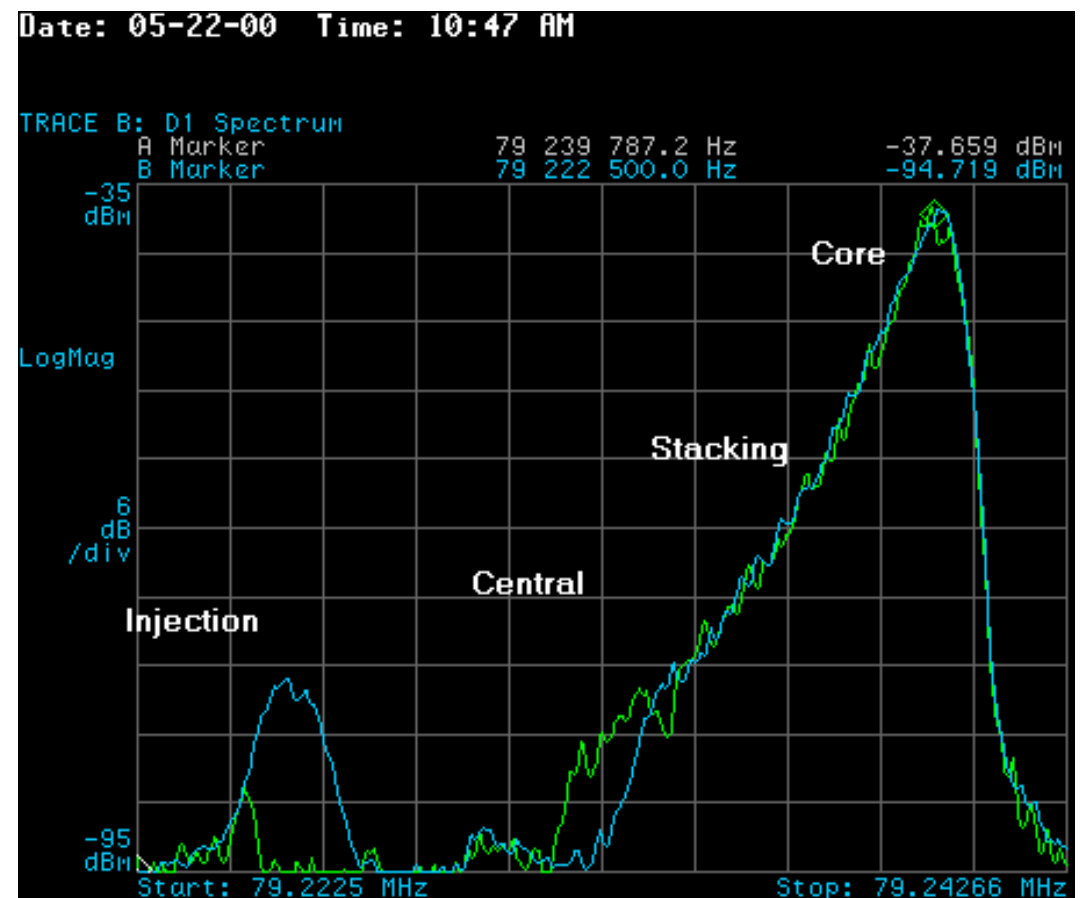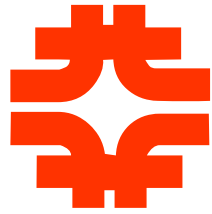Title: ALL TO ALL   Date: 02MAR00 1716

Cooling System: DEB VERTICAL BAND 1
Measurement Type: BETATRON BOTH
Record Number: 25
Beam Current: .02878   mA
Bandwidth (MHz) 0.396007
Phase Delay (pSec)   -2372.51
Phase Offset (Deg) 180.0
Search Range (pSec) 100.0
Search Resolution (pSec)   1.00

Accumulator StackTail Momentum Cooling System

$$\Phi_0 = \frac{|\eta|}{4} \frac{W^2}{f_0} \frac{E_d}{pc} \frac{1}{\ln(f_{max}/f_{min})}$$

Date: 05-22-00   Time: 10:47 AM

TRACE B: D1 Spectrum
A Marker   79 239 787.2 Hz   -37.659 dBm
B Marker   79 222 500.0 Hz   -94.719 dBm

-35 dBm

LogMag

6 dB /div

Core

Stacking

Central

Injection

-95 dBm

Start: 79.2225 MHz   Stop: 79.24266 MHz

2-4 GHz StackTail Momentum System

- 2-4 GHz of Bandwidth
- Physical front end temperature = 80K
- Front end microwave noise temperature ~ 100 K
- Planar Loop pickup arrays with stripline binary combiners
  - ❑ +16 MeV - 256 electrodes
  - ❑ -4 MeV – 48 electrodes
  - ❑ -23 MeV – 16 electrodes
- Planar Loop kicker arrays with microstrip binary combiners
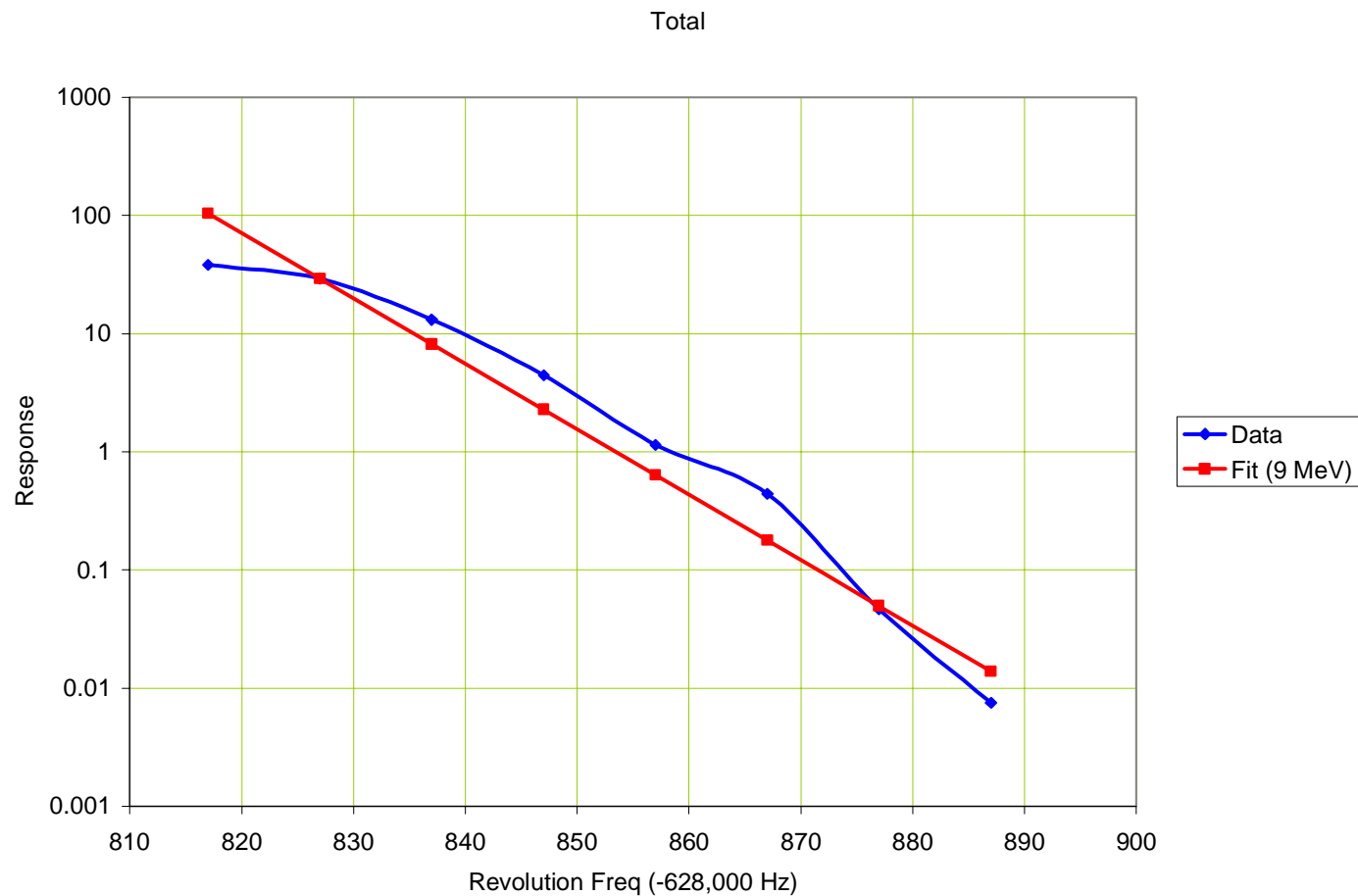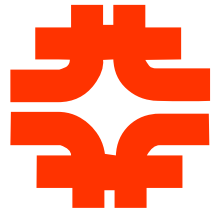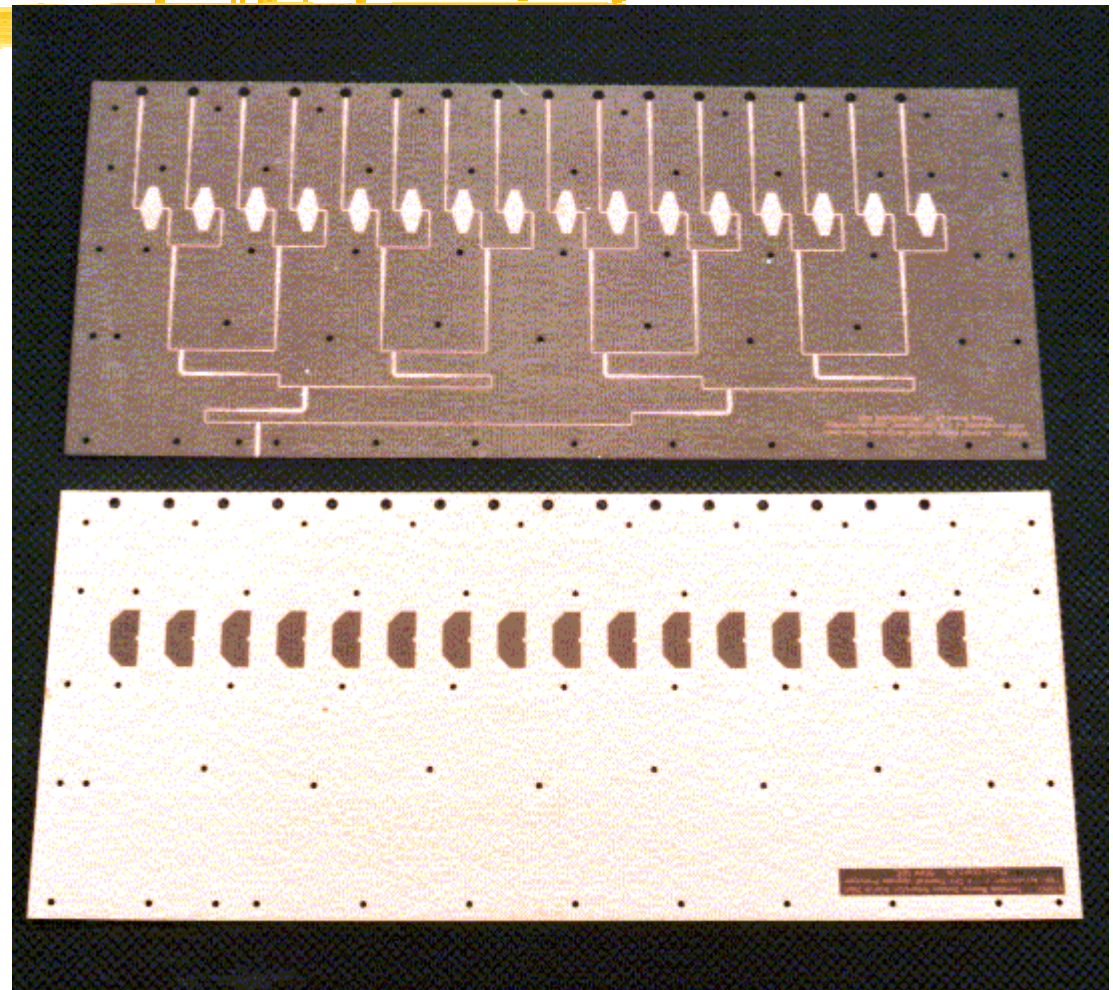- Every 8 electrode pair is powered by a single TWT
- 32 TWTs – 256 electrode pairs
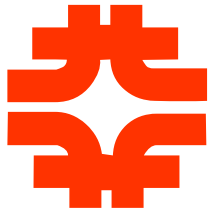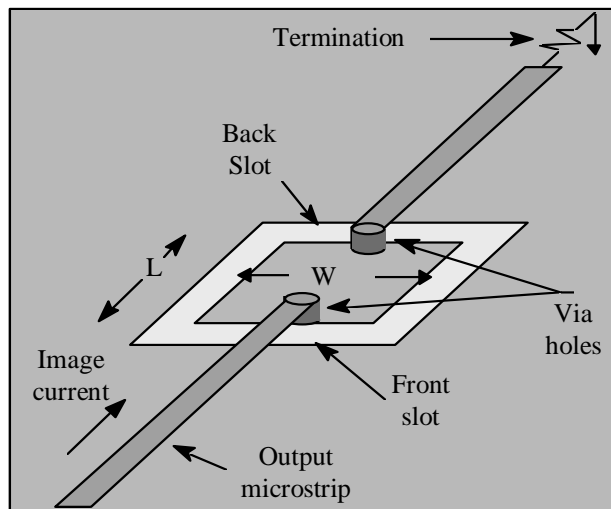
StackTail Frequency Response
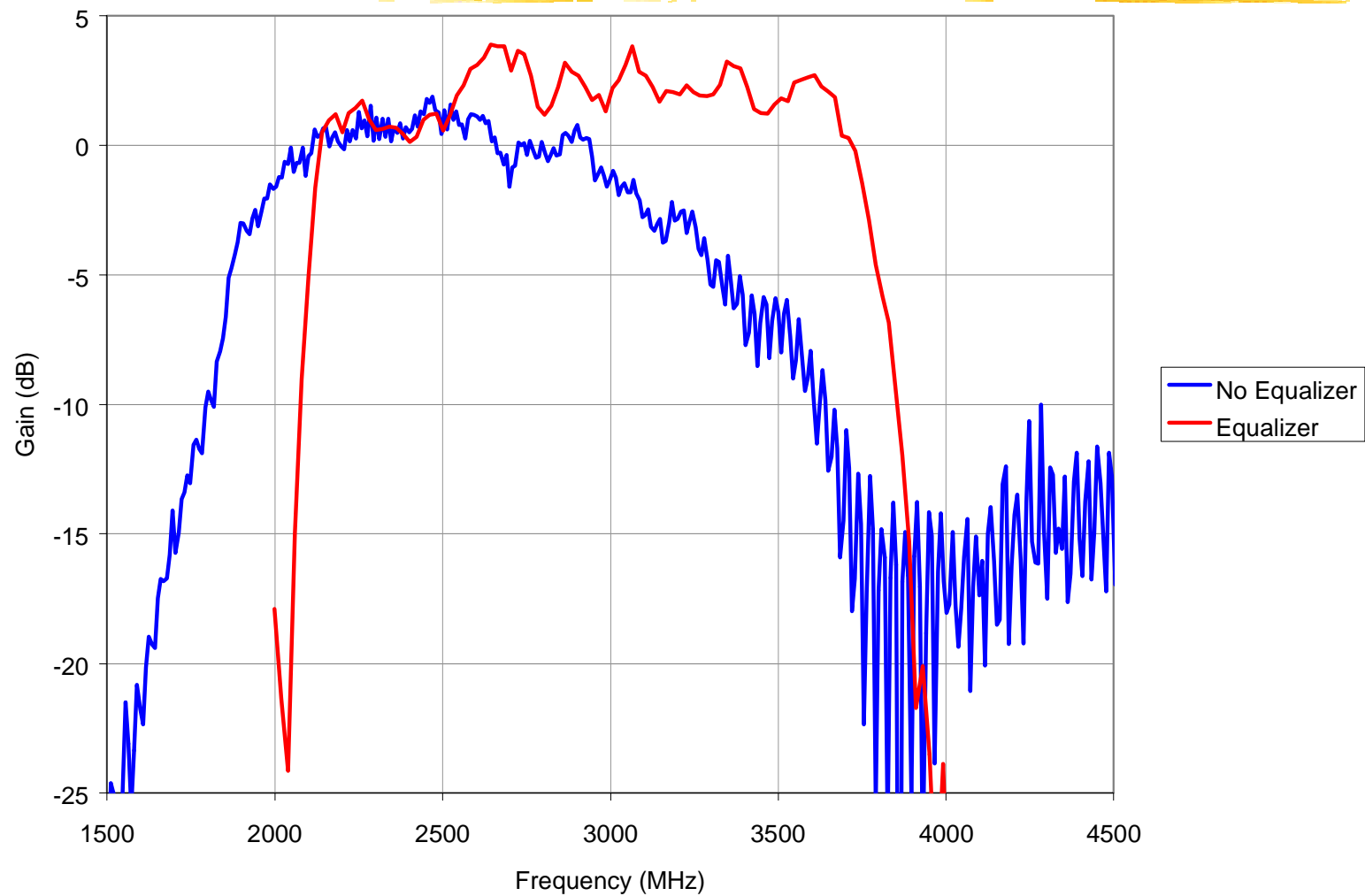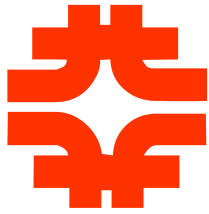
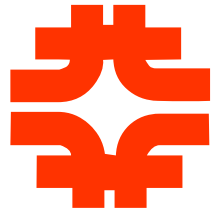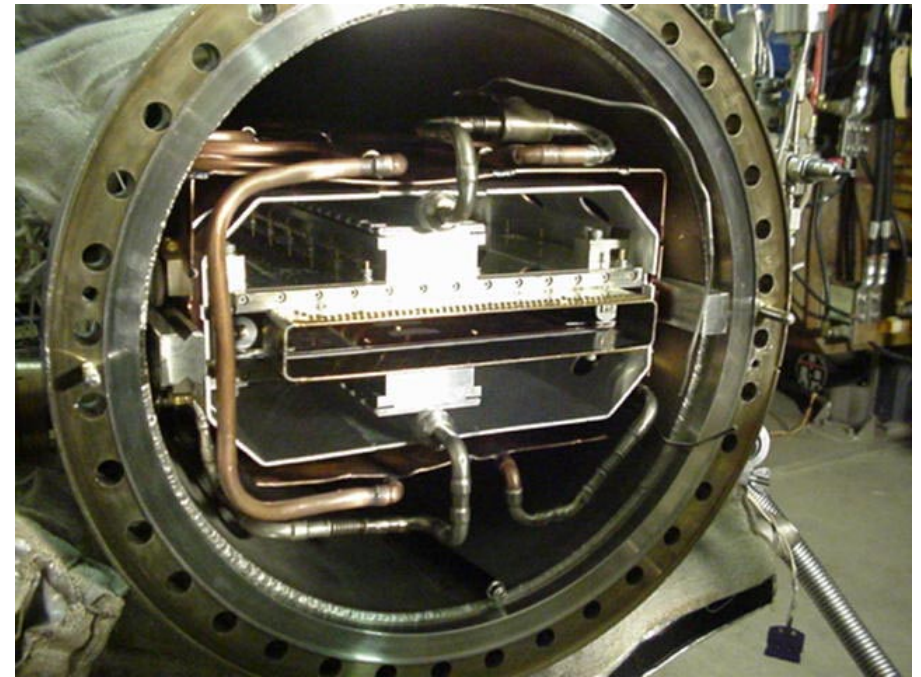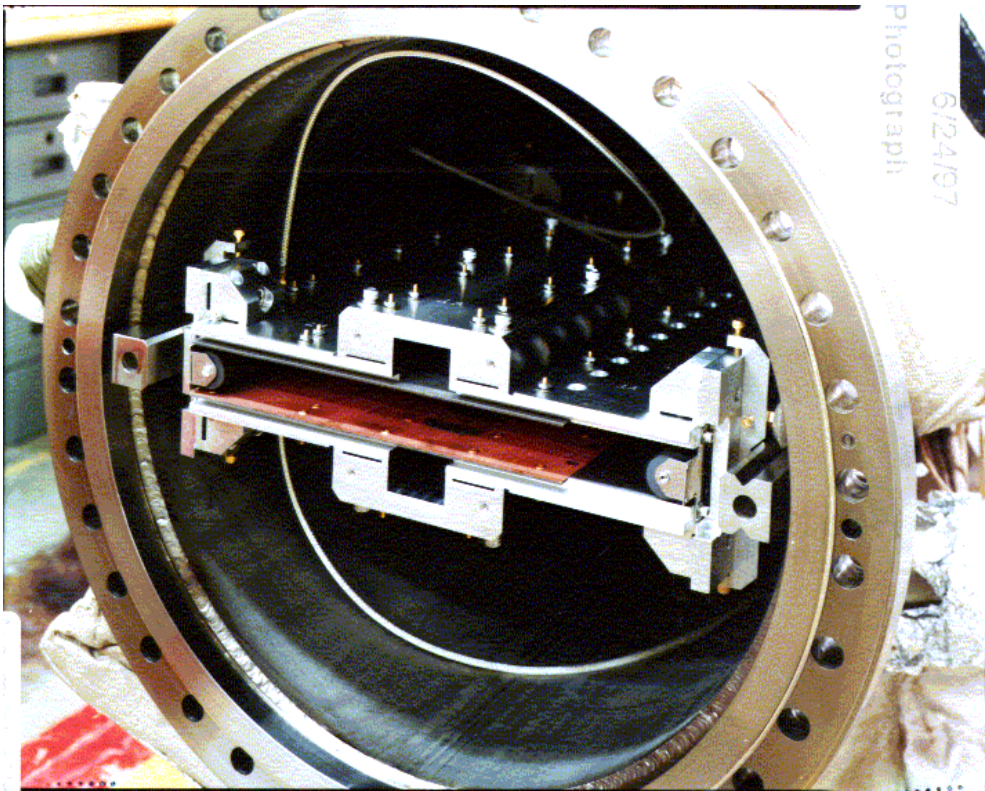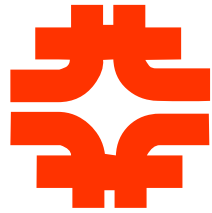# Stacktail Beam Transfer Function Response

Total

Stacktail Pickup tanks

- Stacktail pickup arrays are planar loops but with stripline combiner boards for low loss and low crosstalk
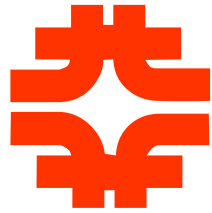
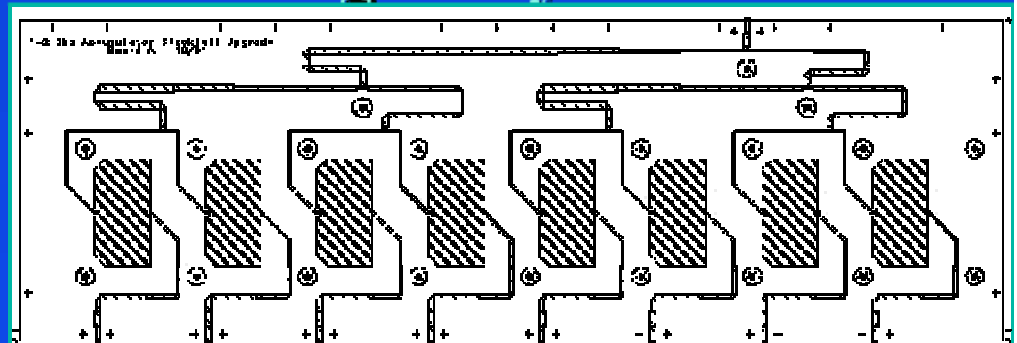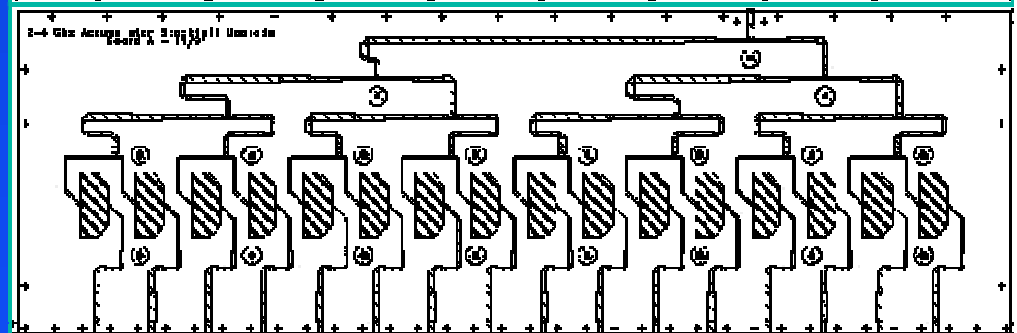# Stacktail Pickup Tanks

Stacktail Pickup Tanks

Stacktail Kicker Tanks

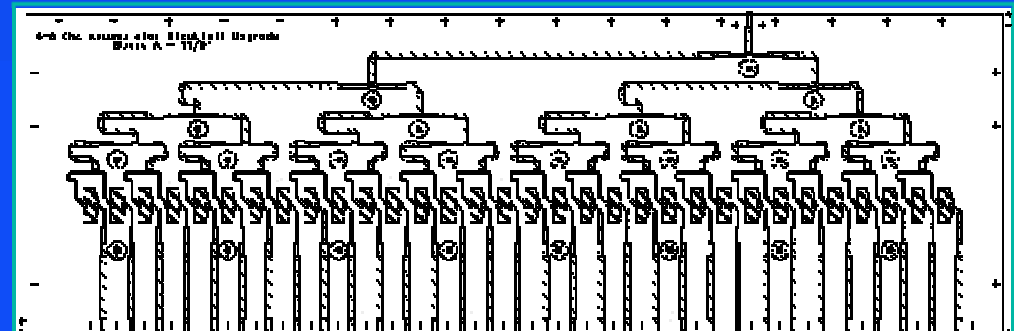- Stacktail planar loop 1-2 GHz circuit board was replaced with already designed 2-4 GHz board
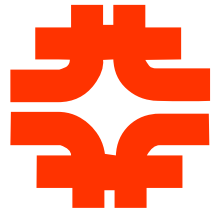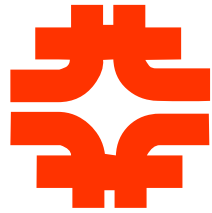

1-2 GHz

2-4 GHz

4-8 GHz

Stacktail Kicker Tank

Accumulator StackTail Upgrade

- Bandwidth increase from 1-2 GHz (Run 1) to 2-4 GHz
  - Microwave components (TWT's, hybrids, etc. are available in octave bandwidths)
- Exponential gain slope E_d (determined by pickup aperture) kept constant.
  - If too small - low stacking rate
  - If too large - large momentum aperture
- η reduced by a factor of two (from 0.022 to 0.012)
  - Zero's in the gain response of the Stacktail system are formed by correlator notch filters.
  - The width of the Schottky bands increase with higher frequency
  - The large phase slope introduced by the notch filters will cause the Stacktail system to be unstable if the Schottky bands become too wide.
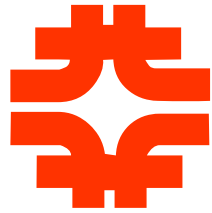
Accumulator Lattice Upgrade
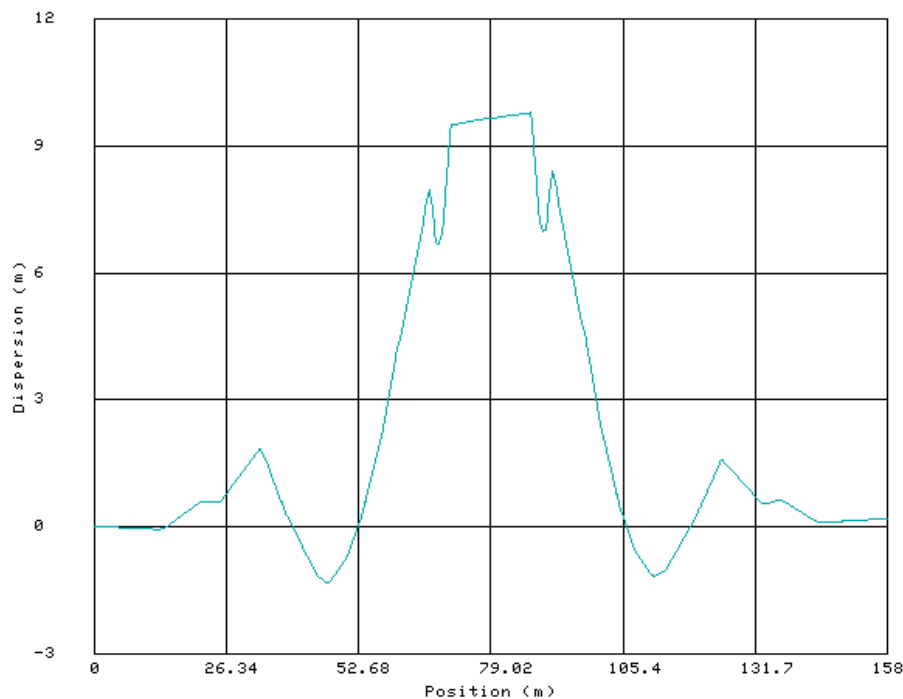
- Goal of the upgrade was to reduce η from 0.022 to 0.012 for Accumulator Stacktail stochastic cooling system stability
- γ_t was increased from 5.41 to 6.52 by decreasing the dispersion in the B7 bend magnets
- Lattice Modifications
  - Individual shunt circuits for all 6 sectors were added to Q3, Q6, Q8, Q10, Q11, Q14 quadrupoles.
  - Six new large quads, Q14, for the high dispersion triplet were made.
  - The current capacity of the shunt circuits for the focusing (QSF1) and defocusing (QSD) busses was increased from 5 to 20A
  - Two Skew sextupoles to compensate the LQ14s were built
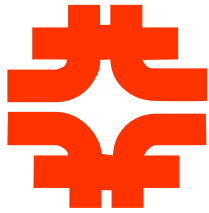
Accumulator Lattice Upgrade
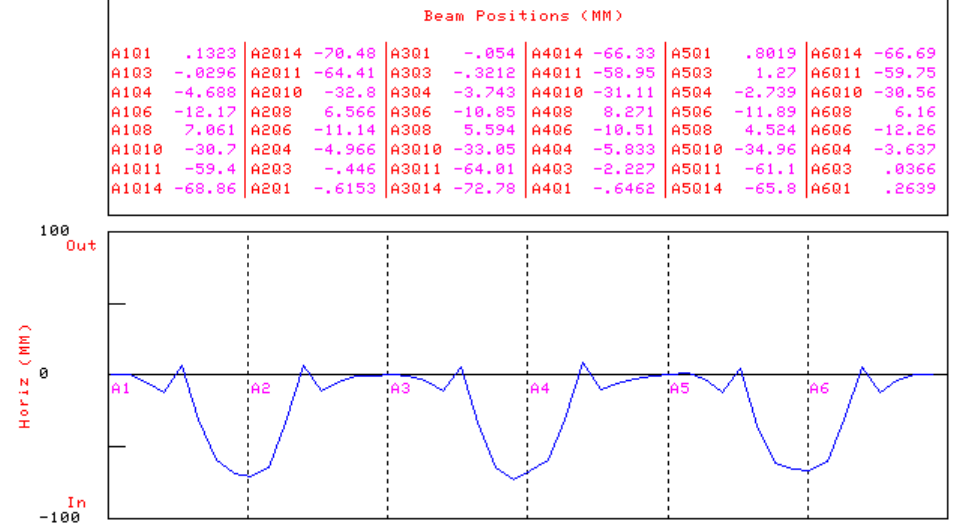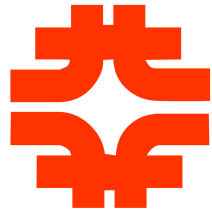# Dispersion Function

Calculation

Measurement

Transverse Heating of the Accumulator Core by the Stacktail

- For a faster rep. rate, the Stacktail gain must be increased to move the beam off the ARF1 drop-off point faster.

- The StackTail kickers have a certain amount transverse kick due to imperfections.

- Different from Run 1, this transverse kick is dominated by a microwave mode at 3.2 GHz with a Q of 50.

- This kick will heat the Accumulator core and must be compensated
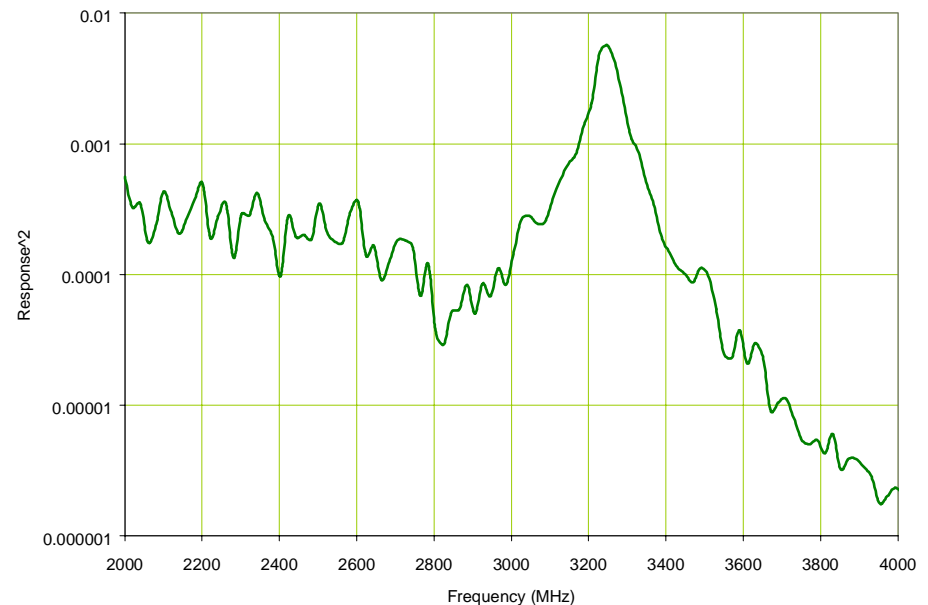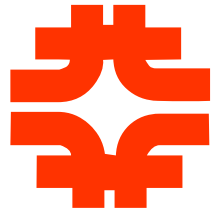
Cross-Talk between the Stacktail and the Core Momentum Systems
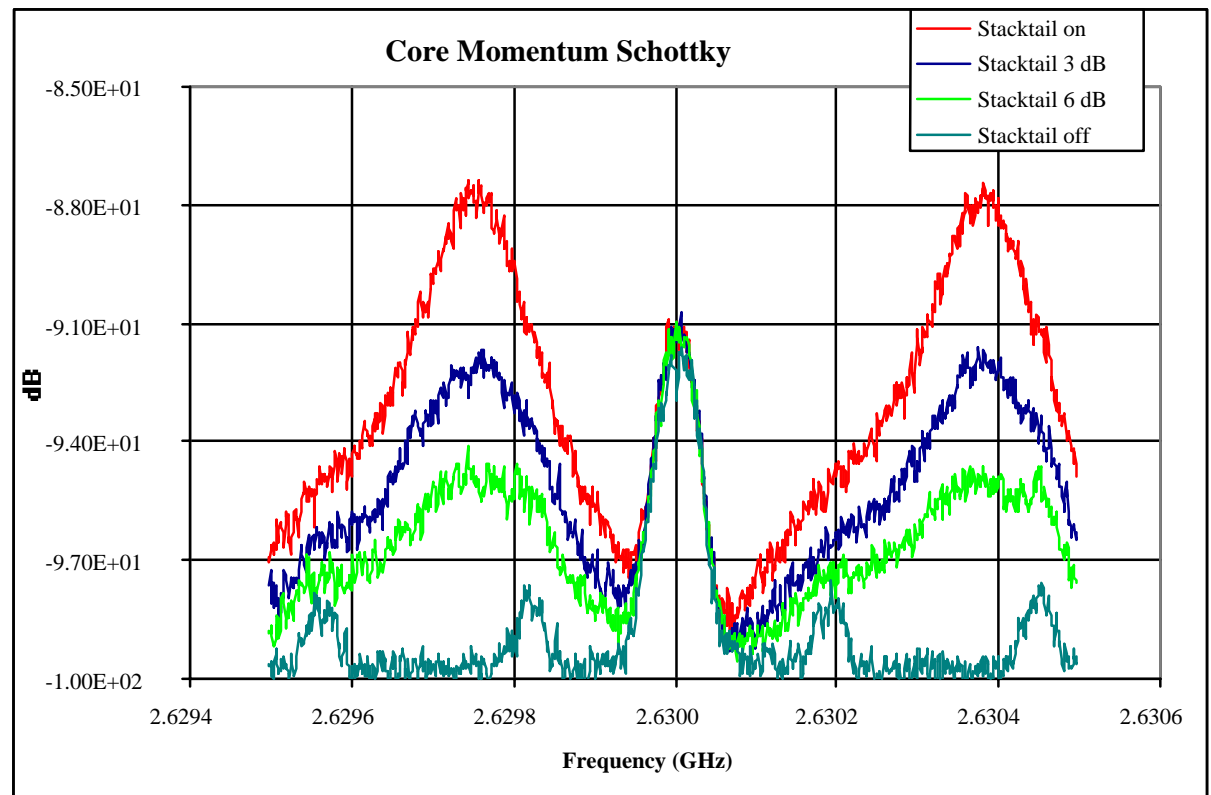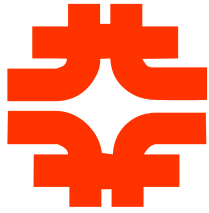
- In Run 1, the Stacktail system at 1-2 GHz did not overlap the core momentum system at 2-4 GHz

- In Run 2, The Stacktail system now completely overlaps the core 2-4 GHz momentum system

- These systems "talk" to each other via the beam severely limiting the stability of the systems.

Core Momentum Schottky

Legend:
- Stacktail on
- Stacktail 3 dB
- Stacktail 6 dB
- Stacktail off

y-axis (dB): -8.50E+01, -8.80E+01, -9.10E+01, -9.40E+01, -9.70E+01, -1.00E+02

x-axis (Frequency (GHz)): 2.6294, 2.6296, 2.6298, 2.6300, 2.6302, 2.6304, 2.6306

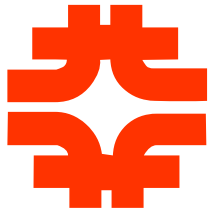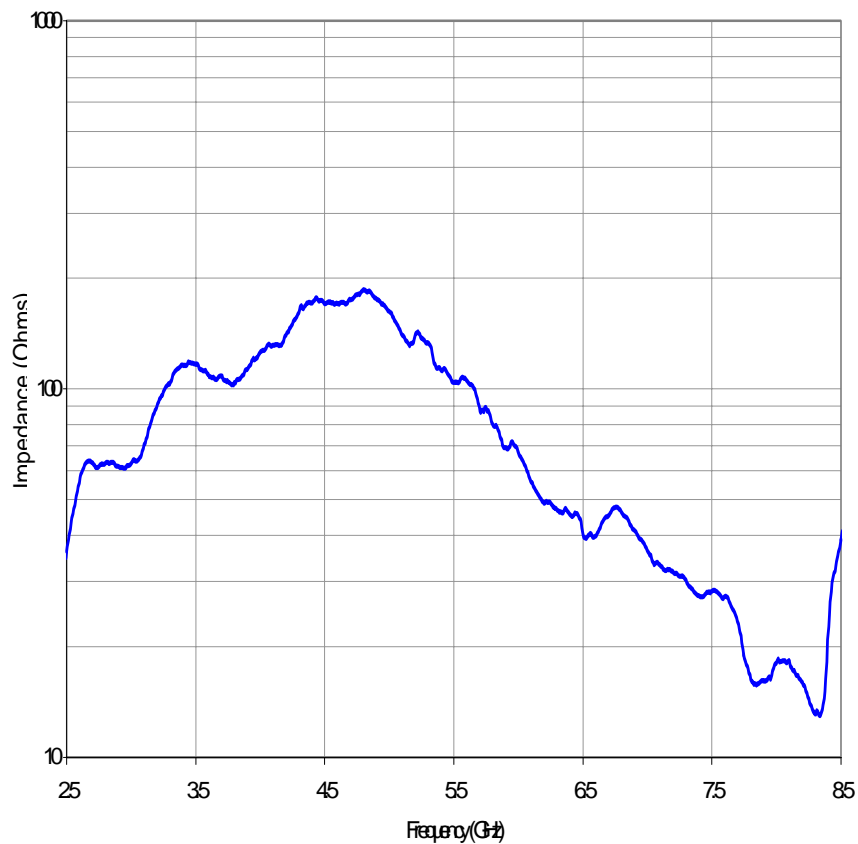# Core 4-8 GHz Betatron Cooling

- The arrays are fabricated with planar loops.
- Beam transfer function measurements show a large gain slope across the band
  - ❑ Usable bandwidth < 1 GHz.
  - ❑ Equalizers will severely limit the dynamic range of the cooling systems.
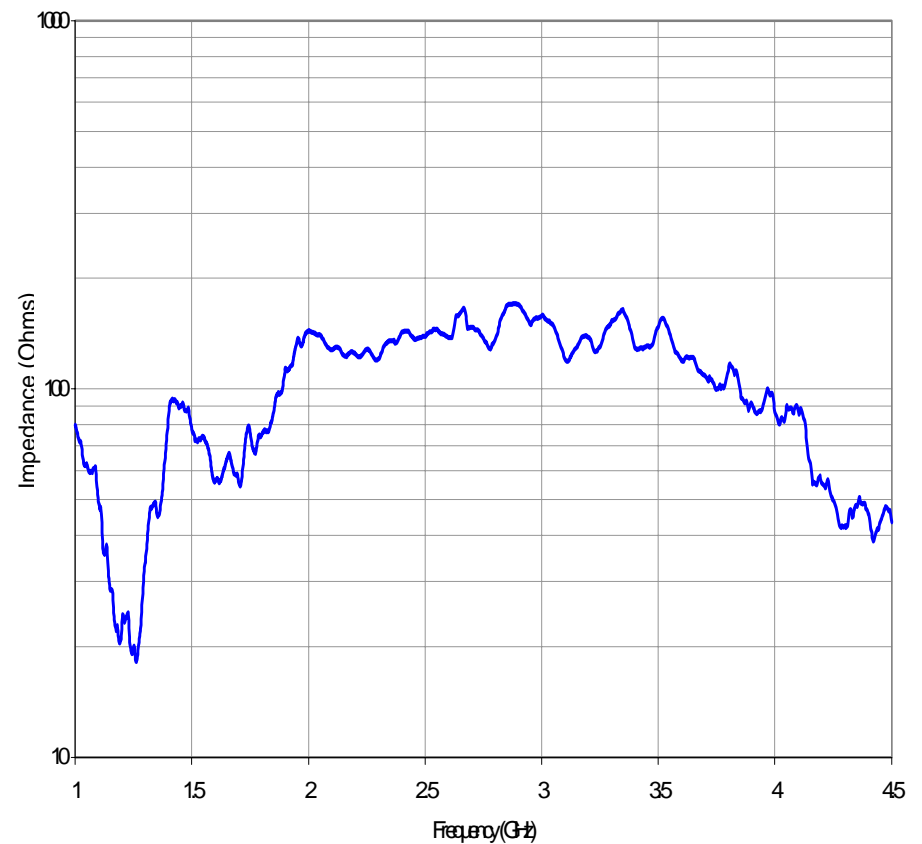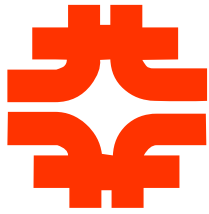- The gain slope is due mostly to the pickups and kickers.
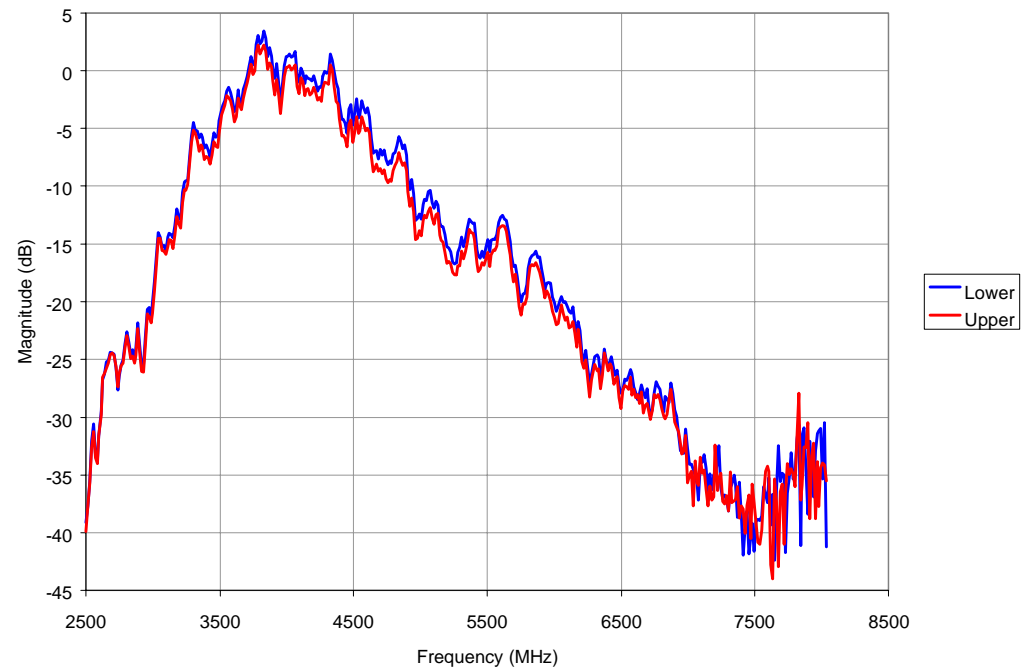
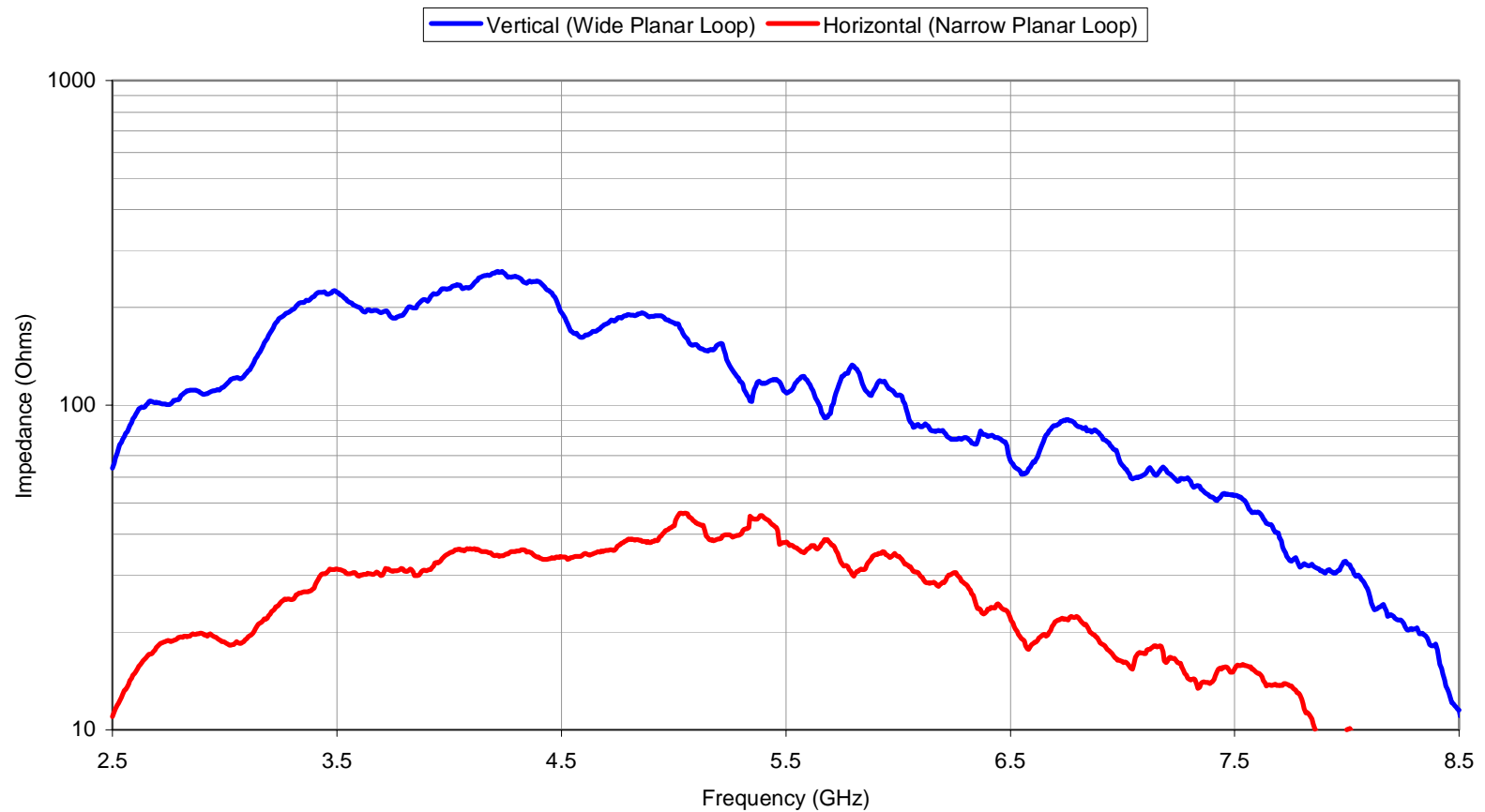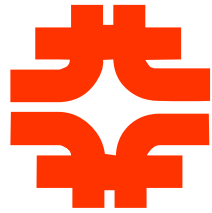# Planar Loop Signal to Noise Measurements

4-8 GHz Planar Loop

### 2-4 GHz Planar Loop

# Planar Loop Signal to Noise Measurements

Recycler Cooling

● The cooling systems are fabricated with 100 Ω planar loops

● The momentum systems use filter cooling.
  ❑ The dispersion in the Recycler is small (~2m)
  ❑ The upper frequency of the cooling system is limited by bad mixing
  ❑ There are 2 momentum bands for extra bandwidth

| Tank	Type	Plane	Center Freq (GHz)	Bandwidth (GHz)	No. Electrodes
1	Momentum	Horizontal	0.75	0.5	8
2	Momentum	Vertical	0.75	0.5	8
3	Momentum	Horizontal	1.5	1	16
4	Momentum	Vertical	1.5	1	16
5	Betatron	Horizontal	3	2	32
6	Betatron	Vertical	3	2	32
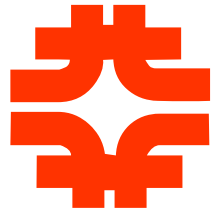
Recycler Cooling Signal Transmission

- The Recycler is 3.3km in circumference and oval in shape
- The smallest chord that can be cut from pickup to kicker is about 1/6 of the ring - 550 meters
- Transmitting microwave signals over coaxial cable would distort the signal (dispersion, gain slope) that would be extremely difficult to correct with equalizers.
- Instead the signal is transmitted by modulating a free-space laser beam
  - ❑ Microwave signal modulates a solid state laser which is connected to an optical fiber
  - ❑ Light wave is launched from the optical fiber into a telescope
  - ❑ Light wave travels about 550 meters in an evacuated pipe
  - ❑ Light wave is collected by a receiving telescope
  - ❑ Light wave is focused on a wideband photodiode and microwave signal is recovered.
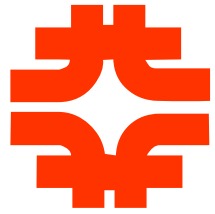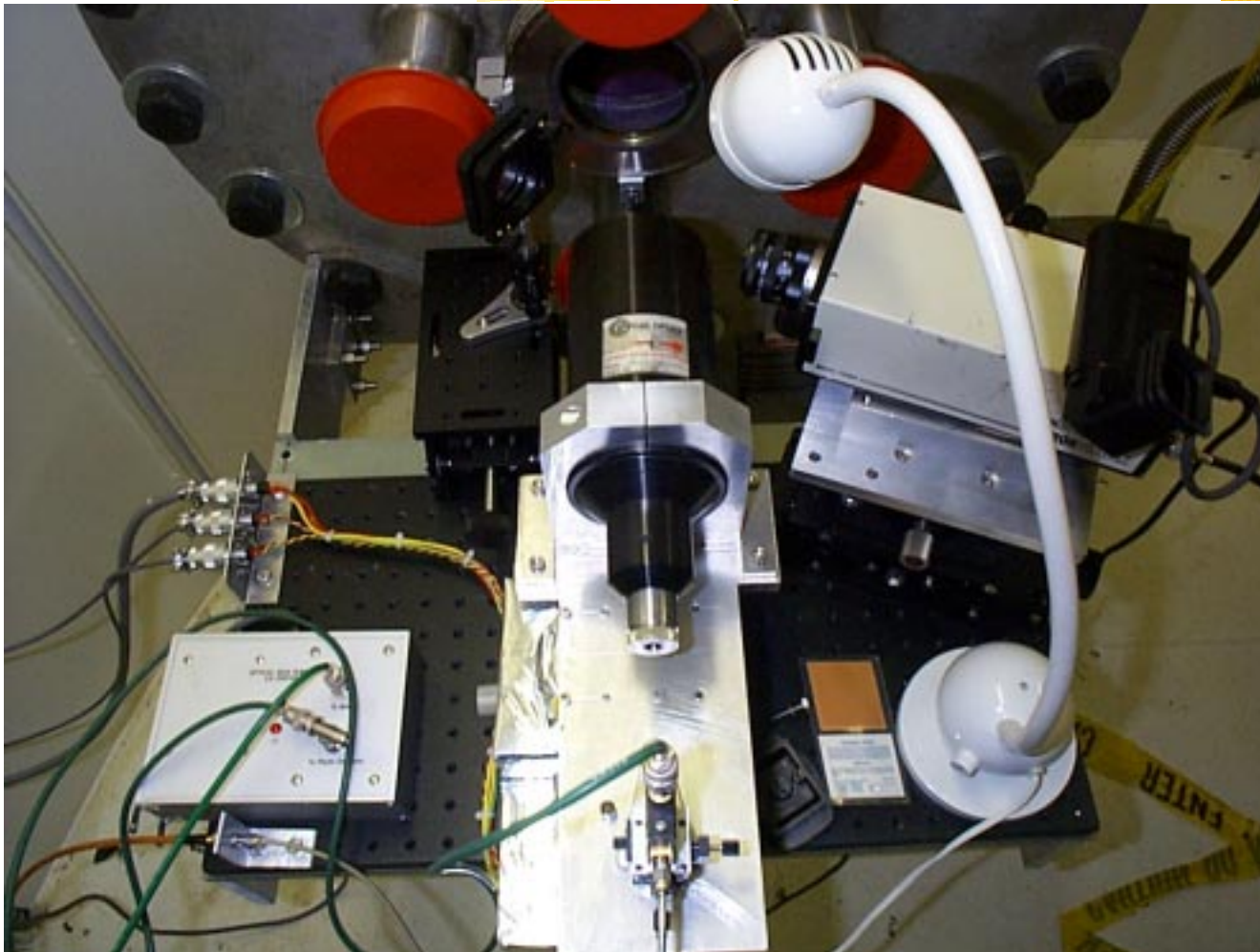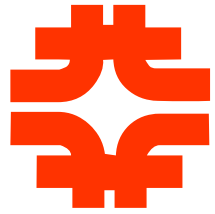
Recycler Cooling Signal Transmitter
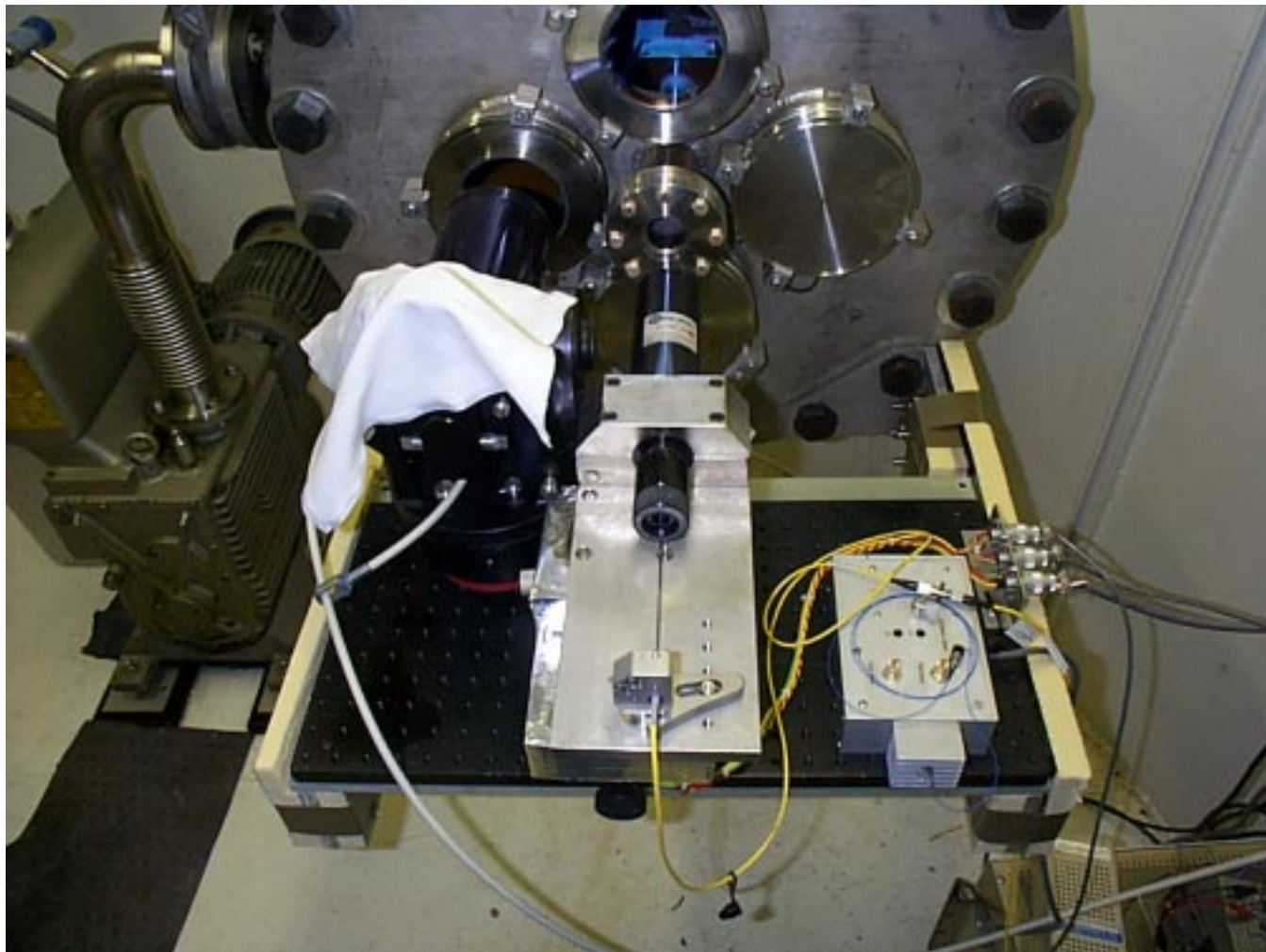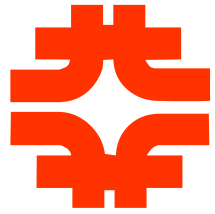
Recycler Cooling Signal Receiver

Recycler Free-Space Laser Beam Pipe